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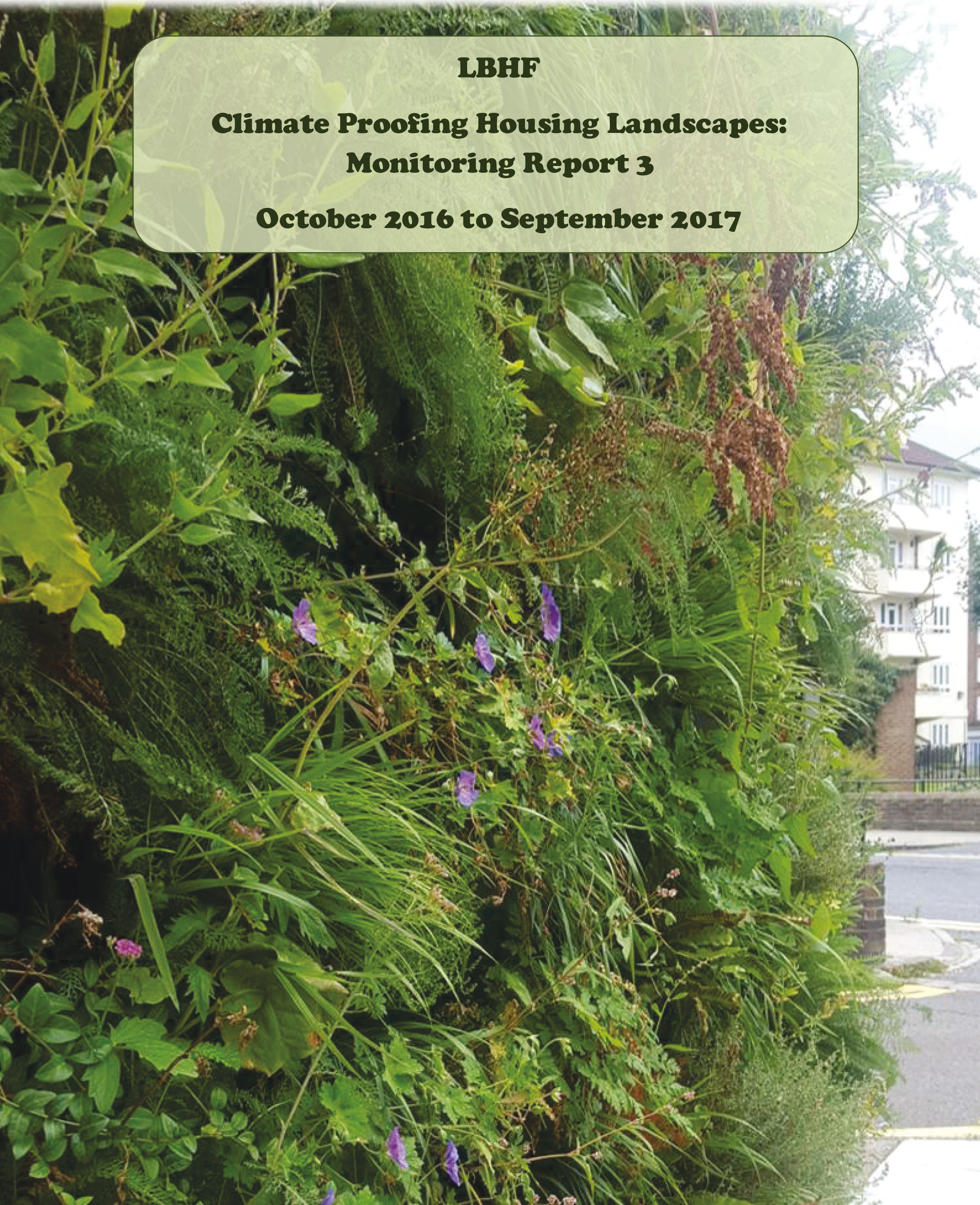

LBHF

Climate Proofing Housing Landscapes: Monitoring Report 3

October 2016 to September 2017

LBHF Climate Proofing Housing Landscapes: Monitoring Report 3 - October 2016 to September 2017

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Non-technical summary

London Borough of Hammersmith and Fulham Climate Proofing Housing Landscape Monitoring Report 3

H&F Council and Groundwork London worked with local residents to design and implement climate change adaptation measures on three housing estates in the borough, making them more resilient and adapted for the future.

Adaptation included the retrofit of a series of Nature-based Solutions to manage stormwater, provide respite areas on hot days, increase residents' contact with nature, and provide opportunities for outdoor activity and social interaction.

In order to ensure that lessons were learned from this process so that similar schemes can be rolled out across London and globally, it was vital that the benefits derived from these interventions were quantified.

The University of East London Sustainability Research Institute were commissioned to carry out a programme of retrofitted monitoring to assess the biodiversity, water attenuation and thermal benefits of the green infrastructure interventions.

Monitoring comprised a combination of time-lapse cameras, flow rate and pressure sensor monitoring, rain simulation, thermal camera images, thermal monitoring, and biodiversity surveys.

Approx. **1,220,900** Litres of rainfall diverted from sewers

A total of **57** species of wildflower and grasses recorded on a single green roof

Max. **39.4%** reduction in temp. on green roof compared to surrounding grey infrastructure

A rain basin passed a test to hold a storm of the size expected once every **100** years

Honey **bees**, bumblebees and solitary bees were all recorded on the wildflowers

Average **82.8%** of rainfall absorbed by green roofs

Time lapse cameras showed that **all** rain flowing into rain basins was absorbed into the soil

1.6°C reduction in heat stress between a vertical rain garden and control brick wall

459% increase in plant species on green roof compared to typical amenity grass lawn

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1. Background

Hammersmith & Fulham Council, in partnership with Groundwork London, worked with local residents to design and implement climate change adaptation measures on three housing estates in the borough, making them more resilient and adapted for the future. Interventions comprised a series of green infrastructure and engineered interventions to:

- manage stormwater
- create urban comfort zones
- support biodiversity
- provide opportunities for grow-your-own initiatives
- make the public realm spaces within the estates more attractive and functional for local residents (Figure 1).

In order to ensure that lessons are learned from this process so that similar schemes can be rolled out across London and globally, it was vital that the benefits derived from these interventions were quantified. As part of this process, the University of East London's Sustainability Research Institute were commissioned to carry out a programme of retrofitted monitoring to assess the biodiversity, water attenuation and thermal benefits of the green infrastructure interventions.

Further background on this project, the monitoring methodologies adopted, and results from the initial monitoring period from August 2015 to September 2016 are detailed in two monitoring reports from this project:

Connop, S. and Clough, J. 2016. LIFE+ Climate Proofing Housing Landscapes: Interim Monitoring Report - August 2015 to May 2016. London: University of East London.

Connop, S., Clough, J., Gunawardena, D. and Nash, C. 2016. LIFE+ Climate Proofing Housing Landscapes: Monitoring Report 2 - June 2016 to September 2016. London: University of East London.

The following report details the results of an additional 12 month monitoring period commissioned by Hammersmith & Fulham Council to investigate the long-term performance of these climate change adaptation measures and to generate data on new measures implemented towards the end of the original project.

Figure 1. Green infrastructure retrofit at Queen Caroline Estate, London Borough of Hammersmith & Fulham. Raised planters, permeable pathways, ornamental planting, pollinator-friendly swales and detention basins.

2. Monitoring methods

Monitoring methods used during this third monitoring period included all of those adopted for the first monitoring period (Connop and Clough 2016; Connop et al. 2016). This comprised:

Stormwater management monitoring

- Time-lapse cameras positioned so that they faced a selection of the key ground level SuDS features (swales and rain gardens) installed at Queen Caroline Estate and Richard Knight House.
- Vantage Vue weather stations installed to monitor the environmental conditions at Queen Caroline Estate and Richard Knight House.
- A series of flowmeters and pressure sensors at Queen Caroline Estate to monitor the fine performance of a selection of the retrofitted green infrastructure components.
- Four pressure sensors were installed at Cheesemans Terrace.
- An additional barologger installed at UEL to act as an atmospheric pressure control.

Storm event simulation

- SuDS designs were proof tested against substantial rainfall events and to assess infiltration rates following such events to generate understanding on how quickly recharge volumes were available following significant rain events.
- This was done by calculating the volume of rainfall for each standard rainfall event in London over a 1 hour period and multiplying this by the as-designed/-built catchment area for each individual SuDS feature that was to be tested. The calculated volume of water was then pumped into each SuDS element selected for testing gradually over a 1 hour period.
- Monitoring equipment already installed at these SuDS features was used, in combination with photography to capture and quantify this performance.

Thermal monitoring

- A FLIR B335 thermal imaging camera was used to capture thermal images of key aspects of the green infrastructure retrofit on particularly hot days and particularly cold days.

Biodiversity monitoring

- Vegetation surveys to assess the colonisation of various green roof components. Including:

  - *Inventory surveys* to record every floral species observed on the roof in order to make a list of all herbaceous species.
  - *Quadrat surveys* to quantify floral change in relation to the experimental treatment plots on Richard Knight House.

Photographic monitoring

- Taking photographic records whilst on site of interesting species and features on retrofitted green infrastructure components.

For further details on these monitoring methods adopted, please refer to the first period monitoring reports (Connop and Clough 2016; Connop et al. 2016).

In addition to these initial monitoring protocols, additional monitoring equipment and an additional monitoring methodology were adopted in the third monitoring period:

Time-lapse camera

An additional time-lapse camera (FPC6) was installed to monitor the Cheeseman Terrace rain gardens (Figure 2).

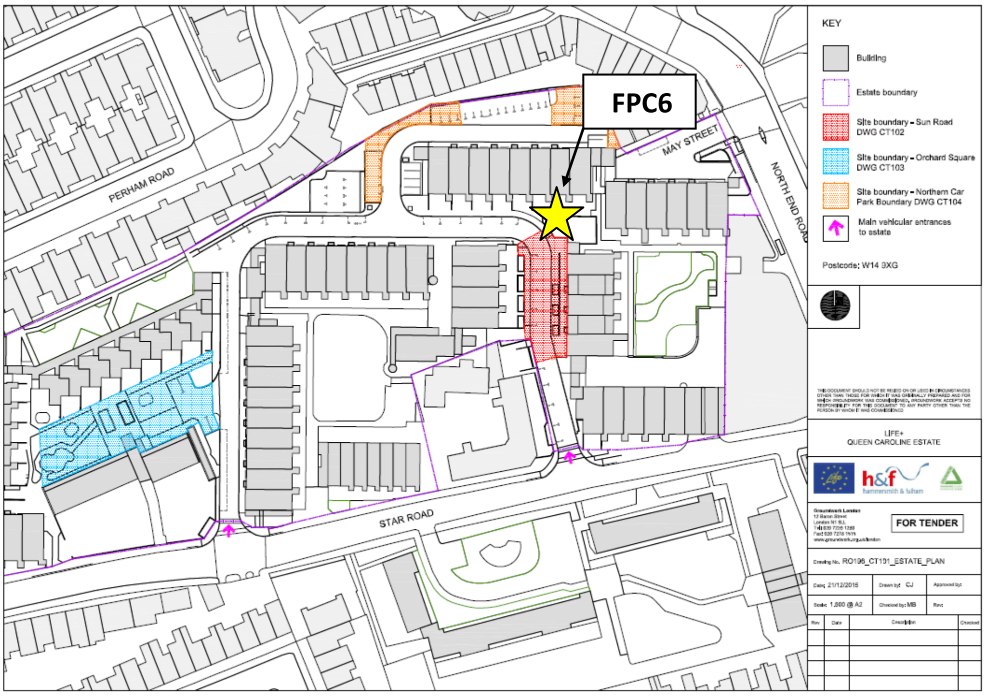


Figure 2. Location of Cheeseman Terrace rain garden time-lapse camera (FPC6), London Borough of Hammersmith and Fulham. On the diagram the area of the rain gardens is represented in red and the fixed point camera is a yellow star.

Urban heat island effect

In order to measure the benefit of the vertical rain garden in terms of providing cooling, an investigation of the temperature reduction created by this feature was carried out. Firstly this was done using a similar technique to that adopted for other green components (i.e. comparison with a control wall using thermal imaging camera). A second method was adopted for this feature to create additional understanding of the distance that any cooling effect could be felt. This is critical in terms of understanding the benefits for the community in terms of how close they would need to be in order to feel a reduction in thermal stress cause by the urban heat island effect.

This was carried out by taking wet bulb temperature measurements at increasing distances from the vertical green wall and a nearby control wall. Measurements were taken using an Extech® Instruments HT30 Heat Stress Meter attached to a tripod. The tripod was then moved away from the wall to set distances measured using a tape measure. The tripod was setup so that the heat stress meter was at approximately chest height for an average person. Wet bulb temperature measurements were used so that a measure of how hot it would feel for somebody standing next to the wall could be measured.

3. Summary of results from October 2016 to September 2017

3.1 Weather patterns during monitoring period

Weather stations at Henrietta House (Queen Caroline Estate) and Richard Knight House were used to generate data on rainfall event size and temperature patterns during the monitoring period. Figure 3 represents some of the data recorded by the Henrietta House weather station. In total 552.4 mm of rain were recorded falling during this period by this weather station.

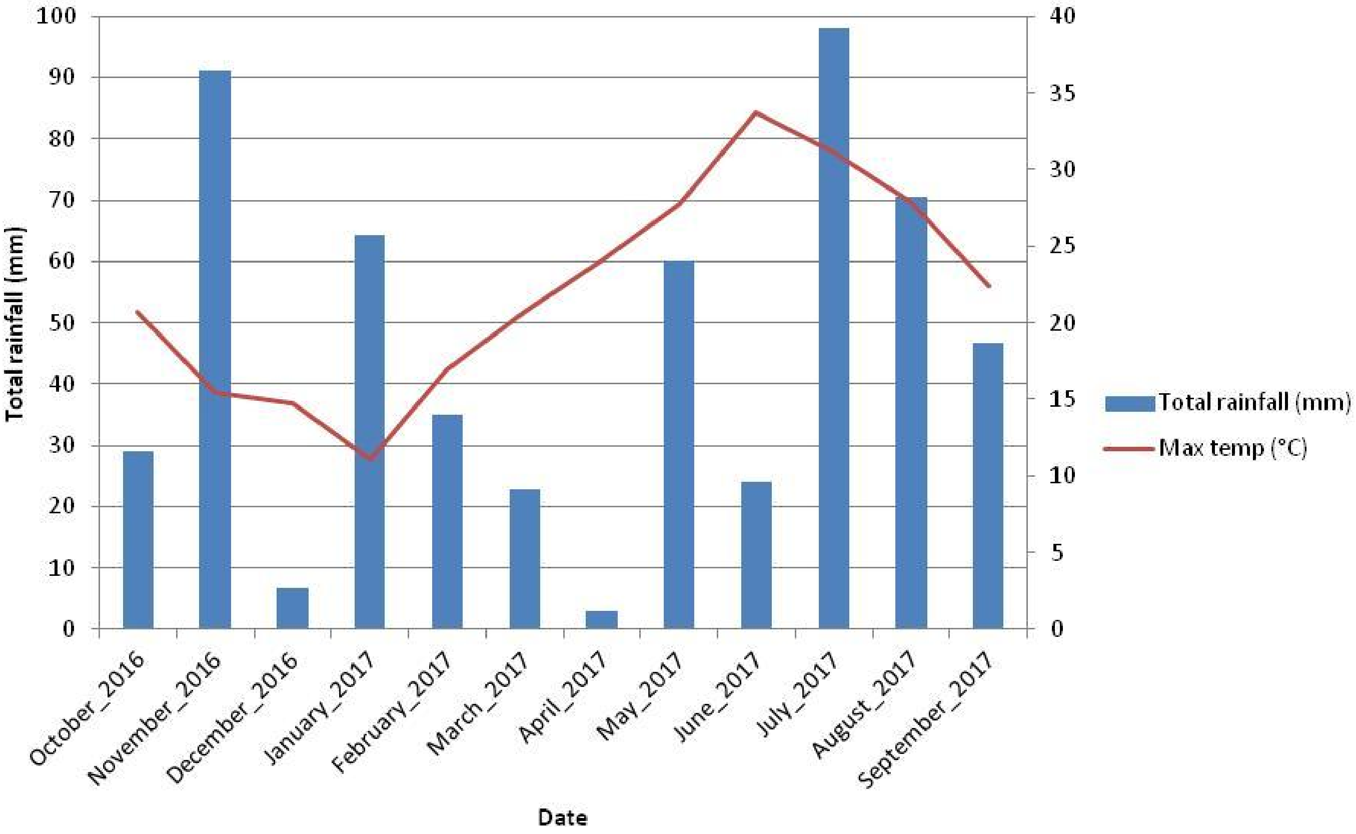


Figure 3. Total rainfall and maximum temperature recorded at the Henrietta House weather station, Queen Caroline Estate, Hammersmith, London from October 2016 to September 2017. Data recorded by a Vantage Vue weather station secured on top of the building.

The wettest month recorded by the Henrietta House weather station was July 2017, followed by November 2016. The five largest rain events (defined as the most rain falling during a 24 hour period) during the winter period (Oct. to March) and the summer period (April to Sept.) were identified (Table 1) for more detailed analysis of SuDS feature performance.

Table 1. Largest rain events recorded by the Henrietta House weather station between October 2016 and September 2017. Events are divided into the top five events during the winter period (Oct 2016 to March 2017) and the summer period (April 2017 to September 2017).

Date	Max temp (°C)	Total rain (mm)	Max rate (mm/hr)
Winter			
09/11/2016	9.1	26.4	12
20/11/2016	8.8	23.4	19.6
12/01/2017	6.8	16	9.2
21/11/2016	12.8	15	22.4
27/02/2017	9.3	12.8	32.2
Summer			
09/08/2017	15.3	30.4	22.4
17/05/2017	18.2	29.2	8.8
30/07/2017	19.8	20	69
22/07/2017	18.9	17.4	46.8
12/07/2017	22.6	16	19.8

Figure 4 represents some of the data recorded by the Richard Knight House weather station. In total, 606.2 mm of rain were recorded falling during this period by this weather station.

Similarly to the Henrietta House station, the wettest month recorded by the Richard Knight House weather station was July 2017, followed by November 2016. The five largest rain events (defined as the most rain falling during a 24 hour period) during the winter period (Oct. to March) and the summer period (April to Sept.) were identified (Table 2) for more detailed analysis of SuDS feature performance.

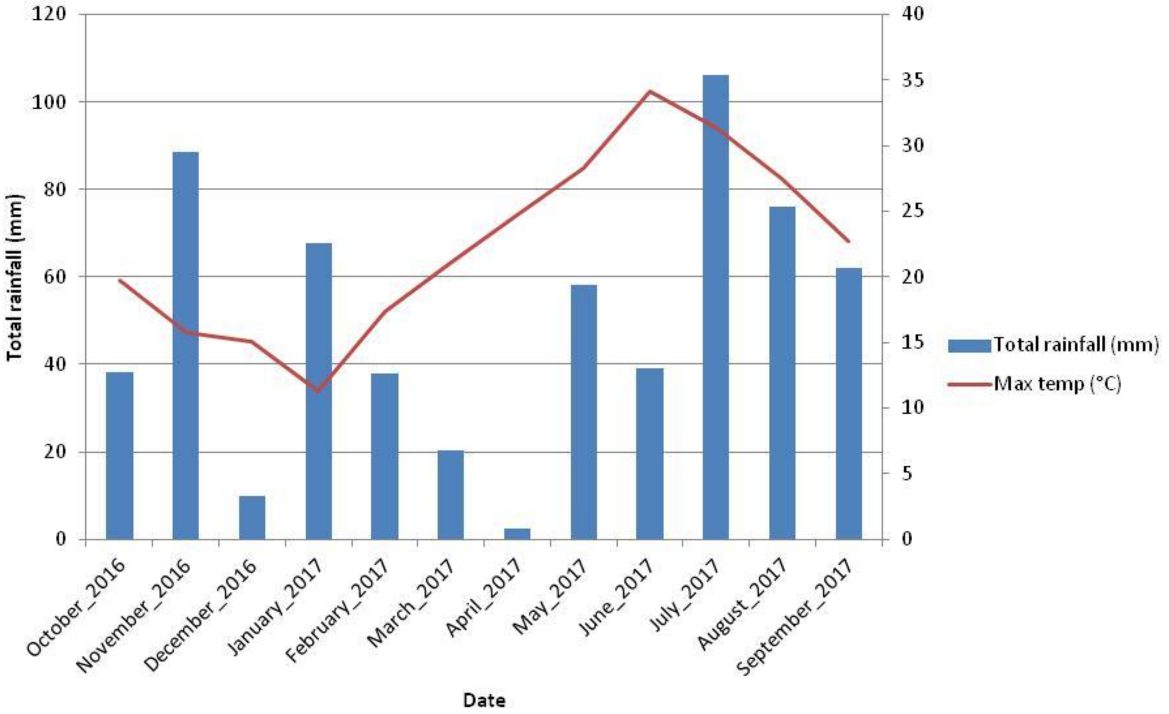


Figure 4. Total rainfall and maximum temperature recorded at the Richard Knight House weather station, Hammersmith, London from October 2016 to September 2017. Data recorded by a Vantage Vue weather station secured on top of the building.

Table 2. Largest rain events recorded by the Richard Knight House weather station between October 2016 and September 2017. Events are divided into the top five events during the winter period (Oct 2016 to March 2017) and the summer period (April 2017 to September 2017).

Date	Max temp (°C)	Total rain (mm)	Max rate (mm/hr)
Winter			
09/11/2016	9.2	24	10.4
20/11/2016	9	23.2	17.6
12/01/2017	7.2	18.8	9
21/11/2016	13.1	16.8	87.2
27/02/2017	9.6	16	30.8
Summer			
09/08/2017	15.4	38	42.6
17/05/2017	18.3	29.2	10.6
30/07/2017	20.6	28.4	86
11/07/2017	19.2	19	33
12/07/2017	21.8	16.8	20

3.2 Fixed-point photo monitoring

During the third monitoring period there were numerous substantial rain events recorded across the monitoring sites. For the ten largest events (five in summer and five in winter), fixed-point camera images were analysed to assess whether any evidence of overflow/fill of the basins could be identified. The top two events for winter and summer are presented here. The other three events for each period are presented in Appendix A.

Winter - Event 1

The largest rain event (defined as mm of rain per 24 hr period) was on the 9th November 2016. For this rain event, a total of 26.4 mm of rain was recorded falling at Henrietta House and 24 mm of rain at Richard Knight House.

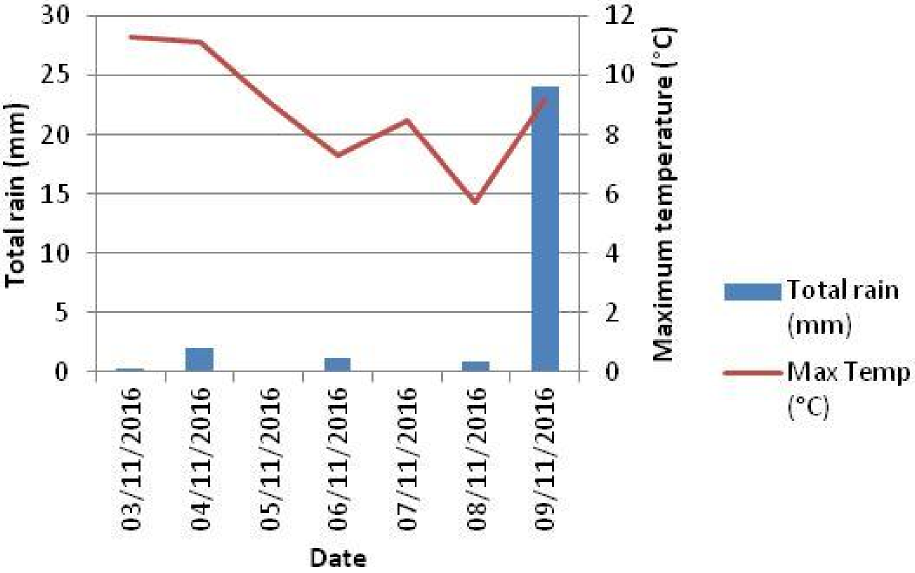
At Richard Knight House, this was a prolonged rain event rather than a short, intense one, preceded by a fairly dry spell (Figure 5). The highest volume and intensity of rainfall during this event fell between 06:00 and 07:00, with the highest rain volume of 4.8 mm in an hour and the highest rain rate recorded as 10.2 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse camera recorded the performance of the SuDS feature at Richard Knight House during this prolonged rain event on the 9th November 2016.

Richard Knight House rain garden (FPC4) performance during 24 mm rain event on 9th November 2016

A complete collection of the images from the Richard Knight House rain garden during the rain event from 00:30 to 10:30 on the 9th November 2016 were captured and analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 06:30, during the peak of the rainfall, despite substantial input from the drainage channel, there was no obvious standing water within or around the rain garden (Figure 6.i). By the time of the first daylight images at 09:00, towards the end of the prolonged rain event, there was also no obvious pooled water (Figure 6.ii) indicating that the rain garden was infiltrating all of the stormwater.

i)



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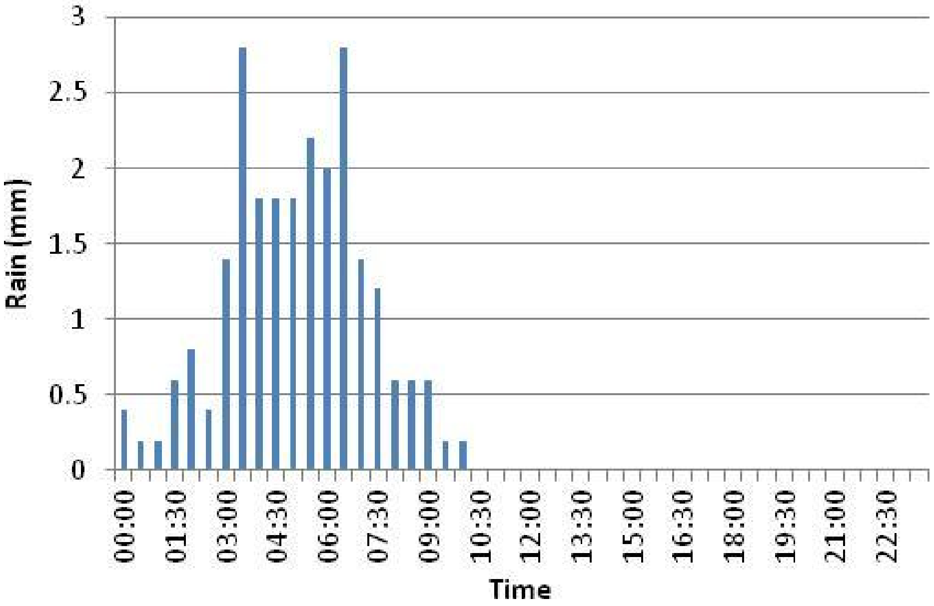


Figure 5. Details of rain event on the 9th November 2016 at Richard Knight House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

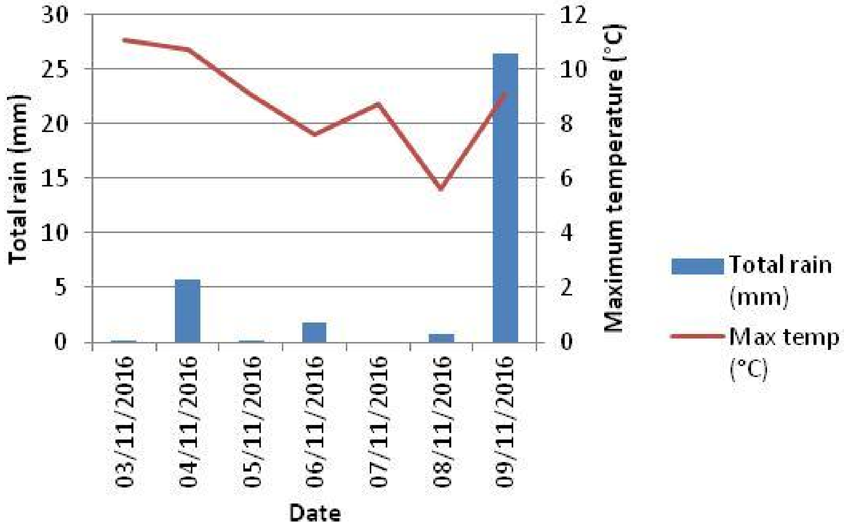
i)

ii)

Figure 6. Time-lapse camera images from Richard Knight House swale (FPC5), 09/11/2016. Images show i) no evidence of overflowing during period of highest rain intensity at 06:40 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 09:02 on the same day.

At Henrietta House, a similar pattern of prolonged rain event preceded by a fairly dry spell was recorded (Figure 7). The highest volume and intensity of rainfall during this event fell between 06:00 and 07:00, with the highest rain volume of 6 mm in an hour and the highest rain rate recorded as 12 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse cameras at Queen Caroline Estate and Cheeseman Terrace recorded the performance of the SuDS features during this prolonged rain event on the 9th November 2016.



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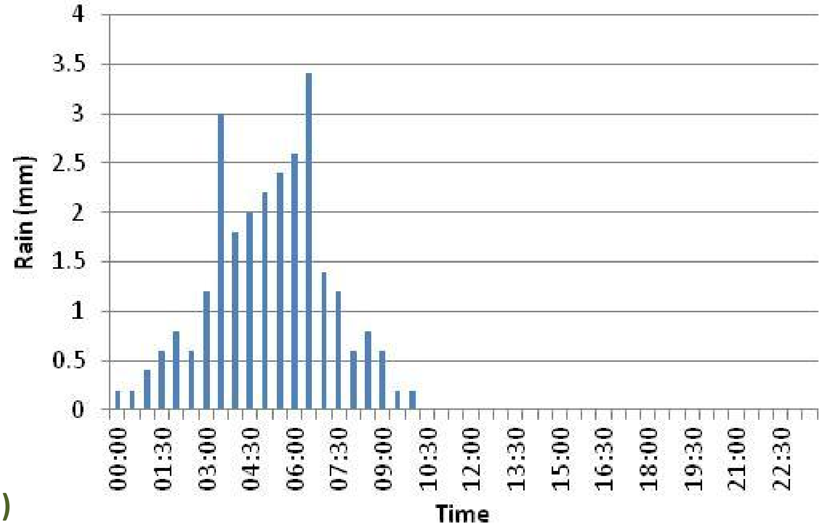


ii)

Figure 7. Details of rain event on the 9th November 2016 at Henrietta House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

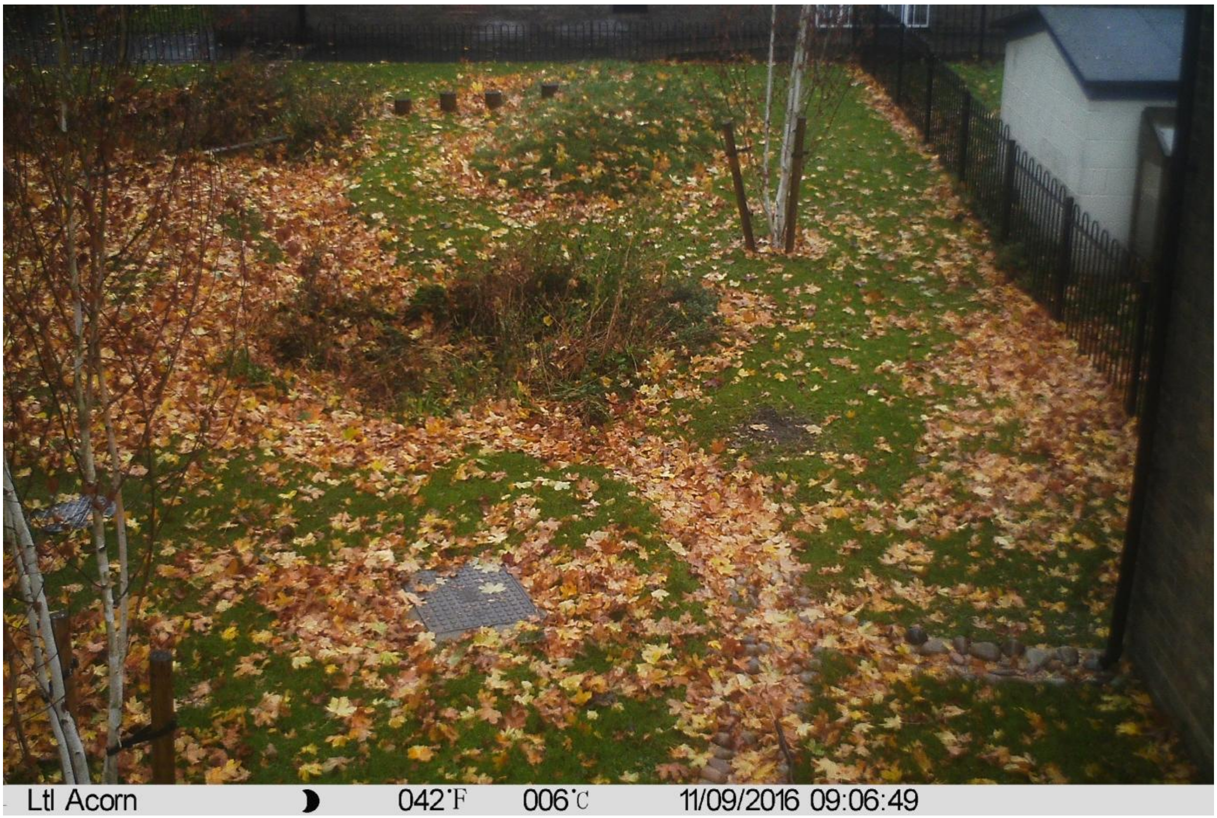
Alexandra House swale (FPC1) performance during 26.4 mm rain event on 9th November 2016

No images were available for the 9th November 2016 rain event for this camera as there was a battery failure.

Community Hall and Sofia House basins (FPC2) performance during 26.4 mm rain event on 9th November 2016

A complete collection of the images from the community hall and Sofia House basins during the rain event from 00:30 to 10:30 on the 9th November 2016 were captured and analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 06:30 during the peak of the rainfall, despite substantial input from the community hall roof, there was no obvious standing water within or around the basin (Figure 8.i). By the time of the first daylight images at 09:00, towards the end of the prolonged rain event, there was also no obvious pooled water (Figure 8.ii) indicating that the basins were infiltrating all of the stormwater.

i) Figure 8. (see below)



ii)

Figure 8. Time-lapse camera images from Community Hall and Sofia House basins (FPC2), 09/11/2016. Images show i) no evidence of overflowing during period of highest rain intensity at 06:50 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 09:06 on the same day.

Adella House grass and stoney basins (FPC3) performance during 26.4 mm rain event on 9th November 2016

An incomplete collection of the images was collected from the Adella House grass and stoney basins during the rain event from 00:30 to 10:30 on the 9th November 2016 due to a camera malfunction. The images that were collected were analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. By the time of the first daylight images at 09:13, towards the end of the prolonged rain event, there was no obvious pooled water (Figure 9) indicating that the basins were infiltrating all of the stormwater.

Figure 9. Time-lapse camera images from Adella House grass and stoney basins (FPC3), 09/11/2016. Image shows no evidence of pooling and evidence of 100% infiltration/conveyance towards the end of the prolonged rain event at 09:13.

Beatrice House swale (FPC4) performance during 26.4 mm rain event on 9th November 2016

No images were available for the 9th November 2016 rain event for this camera as there was a battery failure.

Cheeseman Terrace rain gardens (FPC6) performance during 26.4 mm rain event on 9th November 2016

Due to delays in finalising the new monitoring scope, time-lapse cameras were not installed at Cheeseman Terrace on this date.

Winter - Event 2

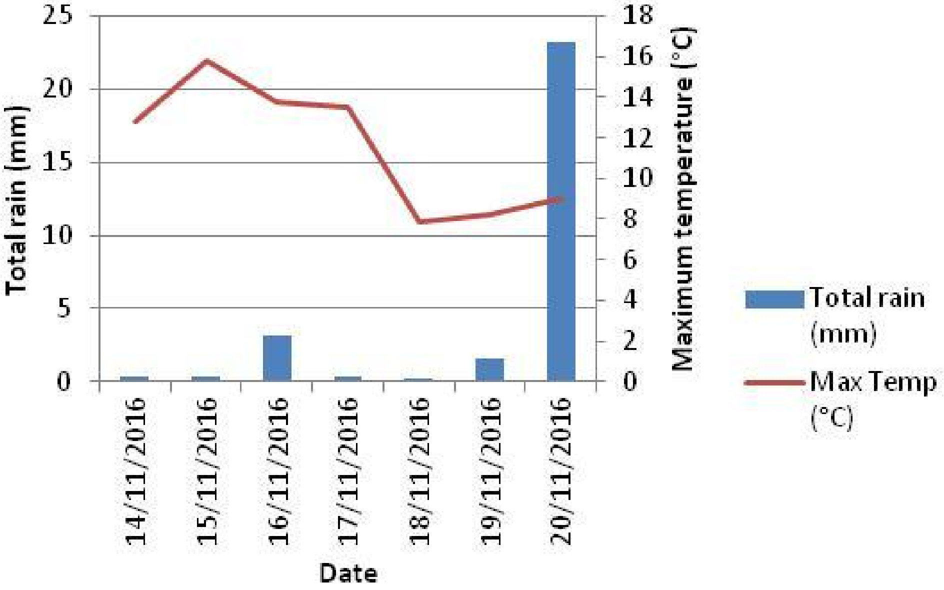
The next largest rain event (defined as mm of rain per 24 hr period) was on the 20th November 2016. For this rain event, a total of 23.4 mm of rain was recorded falling at Henrietta House and 23.2 mm of rain at Richard Knight House.

At Richard Knight House, this was another prolonged rain event rather than a short, intense one. It was divided into two rain spells (am and pm) and was again preceded by a fairly dry spell (Figure 10). The highest volume and intensity of rainfall during this event fell between 05:00 and 06:00, with the highest rain volume of 3.8 mm in an hour and the highest rain rate recorded as 17.6 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse camera recorded the performance of the SuDS feature at Richard Knight House during this prolonged rain event on the 20th November 2016.

Richard Knight House rain garden (FPC4) performance during 23.2 mm rain event on 20th November 2016

A complete collection of the images from the Richard Knight House rain garden during the rain event from 00:30 to 23:30 on the 20th November 2016 were captured and analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 05:30 during the peak of the rainfall, despite substantial input from the neighbouring roofs, there was no obvious standing water within or around the rain garden (Figure 11.i). By the time of the first daylight images at 08:30, following the prolonged rain event, there was also no obvious pooled water (Figure 11.ii) indicating that the rain garden was infiltrating all of the stormwater.



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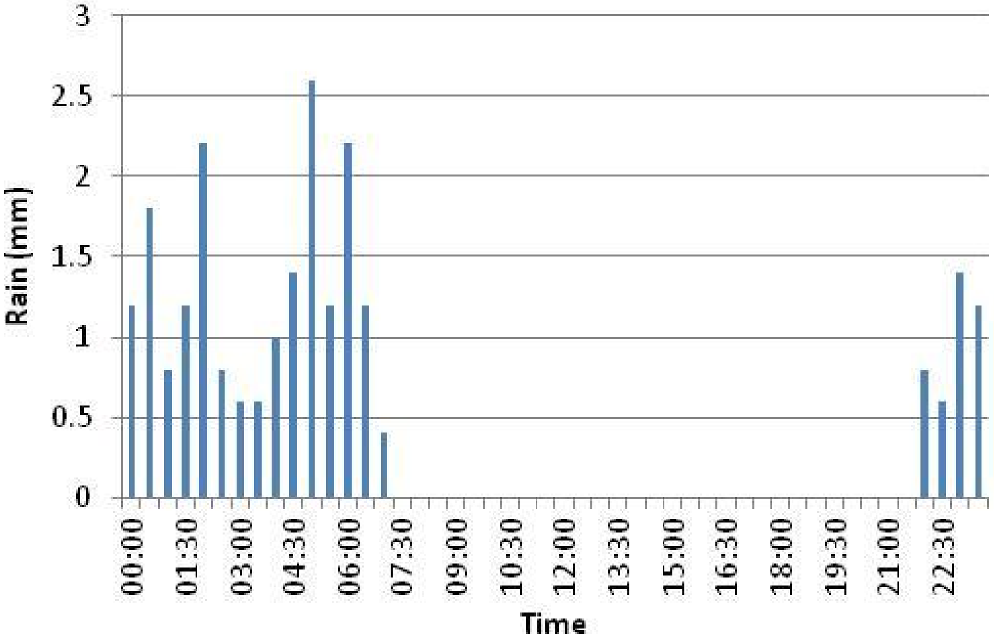


ii)

Figure 10. Details of rain event on the 20th November 2016 at Richard Knight House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes

i)

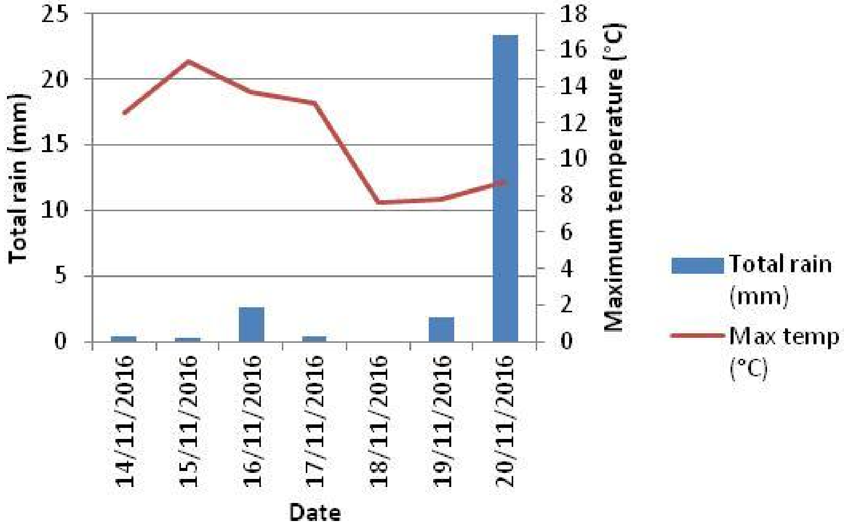
ii)

Figure 11. Time-lapse camera images from Richard Knight House rain garden (FPC5), 20/11/2016. Images show i) no evidence of overflowing during period of highest rain intensity at 05:36 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 08:23 on the same day.

At Henrietta House, a similar pattern of prolonged rain event preceded by a fairly dry spell was recorded (Figure 12). The highest volume and intensity of rainfall during this event fell between 05:00 and 06:00, with the highest rain volume of 4.4 mm in an hour and the highest rain rate recorded as 19.6 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse cameras at Queen Caroline Estate and Cheeseman Terrace recorded the performance of the SuDS features during this prolonged rain event on the 20th November 2016.

i)



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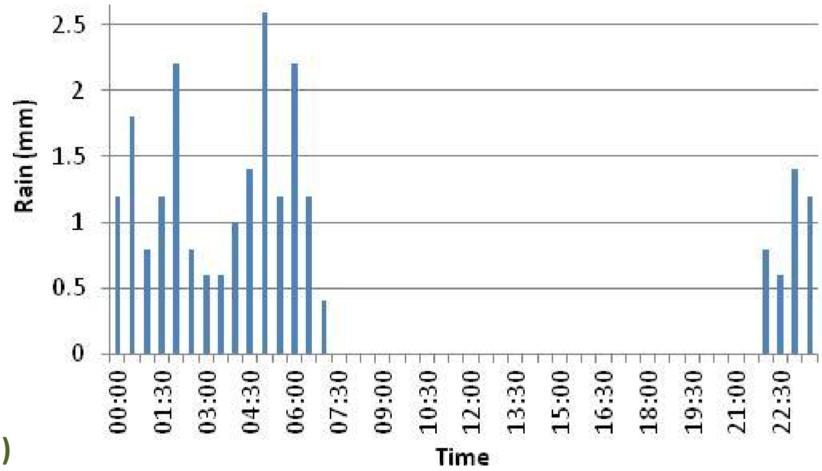


Figure 12. Details of rain event on the 20th November 2016 at Henrietta House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes

Alexandra House swale (FPC1) performance during 23.4 mm rain event on 20th November 2016

No images were available for the 20th November 2016 rain event for this camera as there was a battery failure.

Community Hall and Sofia House basins (FPC2) performance during 23.4 mm rain event on 20th November 2016

A complete collection of the images from the community hall and Sofia House basins during the rain event from 00:30 to 23:30 on the 20th November 2016 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 04:30 during the peak of the rainfall, despite substantial input from the community hall roof, there was no obvious standing water within or around the basin (Figure 13.i). By the time of the first daylight images at 08:30, following the more substantial part of the prolonged rain event, there was also no obvious pooled water (Figure 13.ii) indicating that the basins were infiltrating all of the stormwater.

i) Figure 13. (see below)

ii)

Figure 13. Time-lapse camera images from Community Hall and Sofia House basins (FPC2), 20/11/2016. Images show i) no evidence of overflowing during a period of high rain intensity at 04:21 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 08:41 on the same day.

Adella House grass and stoney basins (FPC3) performance during 23.4 mm rain event on 20th November 2016

An incomplete collection of the images was collected from the Adella House grass and stoney basins during the rain event from 00:30 to 23:30 on the 20th November 2016 due to a camera malfunction. The images that were collected were analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. By the time of the first daylight images at 08:24, towards the end of the first more substantial part of the prolonged rain event, there was no obvious pooled water (Figure 14) indicating that the basins were infiltrating all of the stormwater.

Figure 14. Time-lapse camera images from Adella House grass and stoney basins (FPC3), 20/11/2016. Image shows no evidence of pooling and evidence of 100% infiltration/conveyance towards the end of the prolonged rain event at 08:24.

Beatrice House swale (FPC4) performance during 23.4 mm rain event on 20th November 2016

No images were available for the 20th November 2016 rain event for this camera as there was a battery failure.

Cheeseman Terrace rain gardens (FPC6) performance during 23.4 mm rain event on 20th November 2016

Due to delays in finalising the new monitoring scope, time-lapse cameras were not installed at Cheeseman Terrace on this date.

Analysis of the other three largest rain events from the winter monitoring period are displayed in Appendix A1.

Summer - Event 1

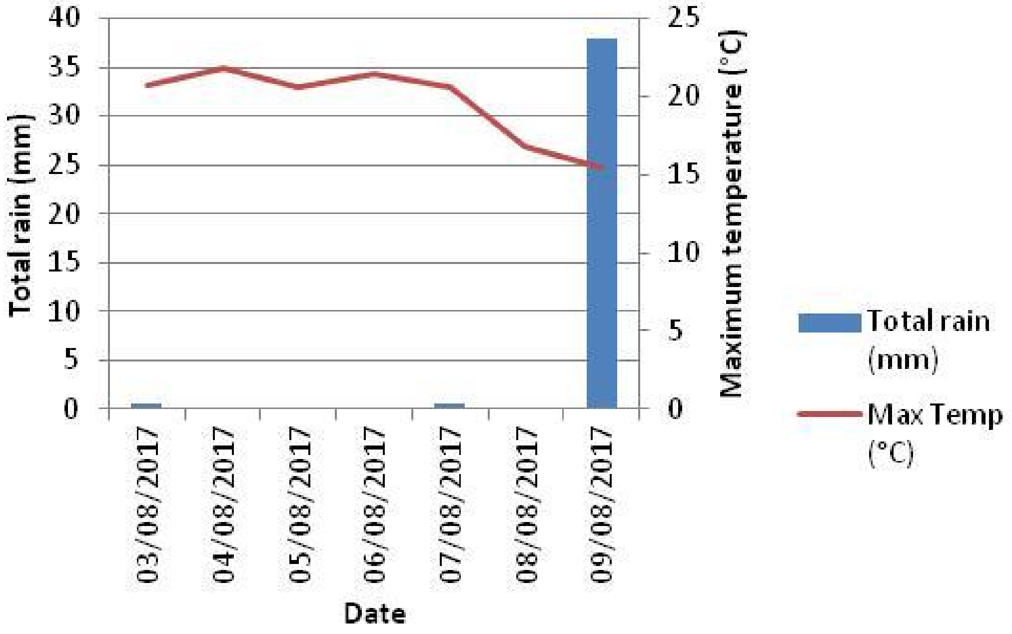
The largest rain event in summer (defined as mm of rain per 24 hr period) was on the 9th August 2017. For this rain event, a total of 30.4 mm of rain was recorded falling at Henrietta House and 38 mm of rain at Richard Knight House.

At Richard Knight House, this was a prolonged rain event with an intense period of rain at the beginning. The weather preceding the event was dry and warm (Figure 15). The highest volume and intensity of rainfall during this event fell between 11:00 and 12:00, with the highest rain volume of 10.6 mm in an hour and the highest rain rate recorded as 42.6 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

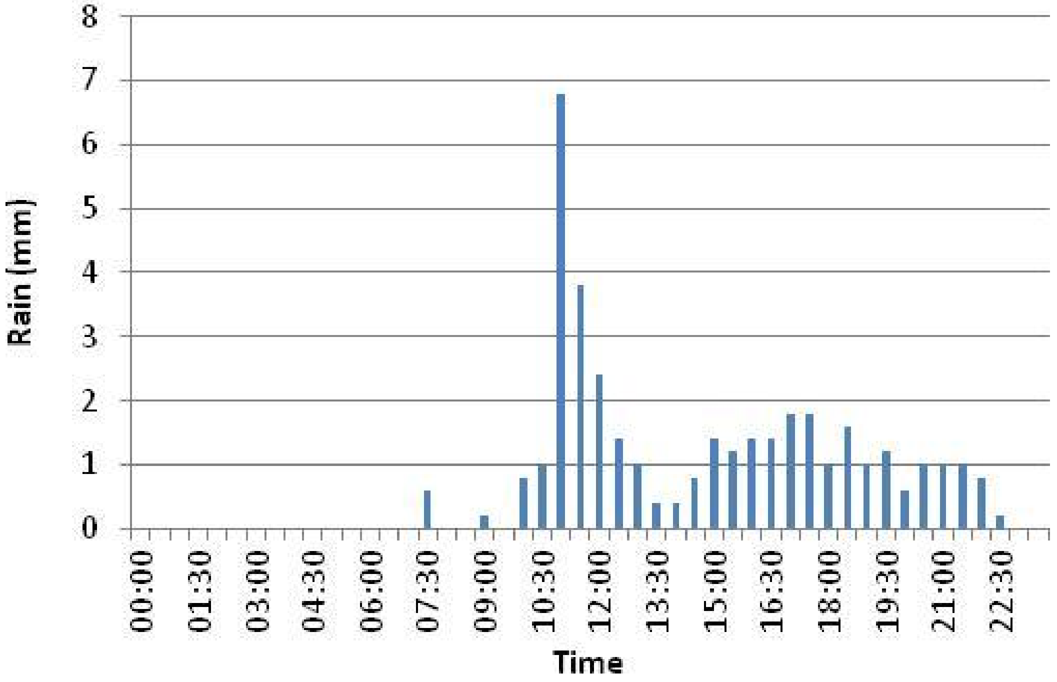
The time-lapse camera recorded the performance of the SuDS feature at Richard Knight House during this prolonged rain event on the 9th August 2017.

Richard Knight House rain garden (FPC4) performance during 38 mm rain event on 9th August 2017

A complete collection of the images from the Richard Knight House rain garden during the rain event from 07:30 to 23:00 on the 9th August 2017 were captured and analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 11:00 during the peak of the rainfall, despite substantial input from the neighbouring roofs, there was no obvious standing water around the rain garden (Figure 16.i). By the time of the end of the rain event at 23:59, there was also no obvious pooled water (Figure 16.ii) indicating that the rain garden was infiltrating all of the stormwater.



i)



ii)

Figure 15. Details of rain event on the 9th August 2017 at Richard Knight House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes

Figure 16. Time-lapse camera images from Richard Knight House rain garden (FPC5), 09/08/2017. Images show i) no evidence of overflowing during period of highest rain intensity at 10:37 and ii) evidence of 100% infiltration/conveyance by the end of the rain event at 23:59 on the same day.

At Henrietta House, a similar pattern of a more intense rain event preceded by damper weather was recorded (Figure 17). The highest volume and intensity of rainfall during this event fell between 10:30 and 11:30, with the highest rain volume of 5 mm in an hour and the highest rain rate recorded as 22.4 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse cameras at Queen Caroline Estate and Cheeseman Terrace recorded the performance of the SuDS features during this prolonged rain event on the 9th August 2017.

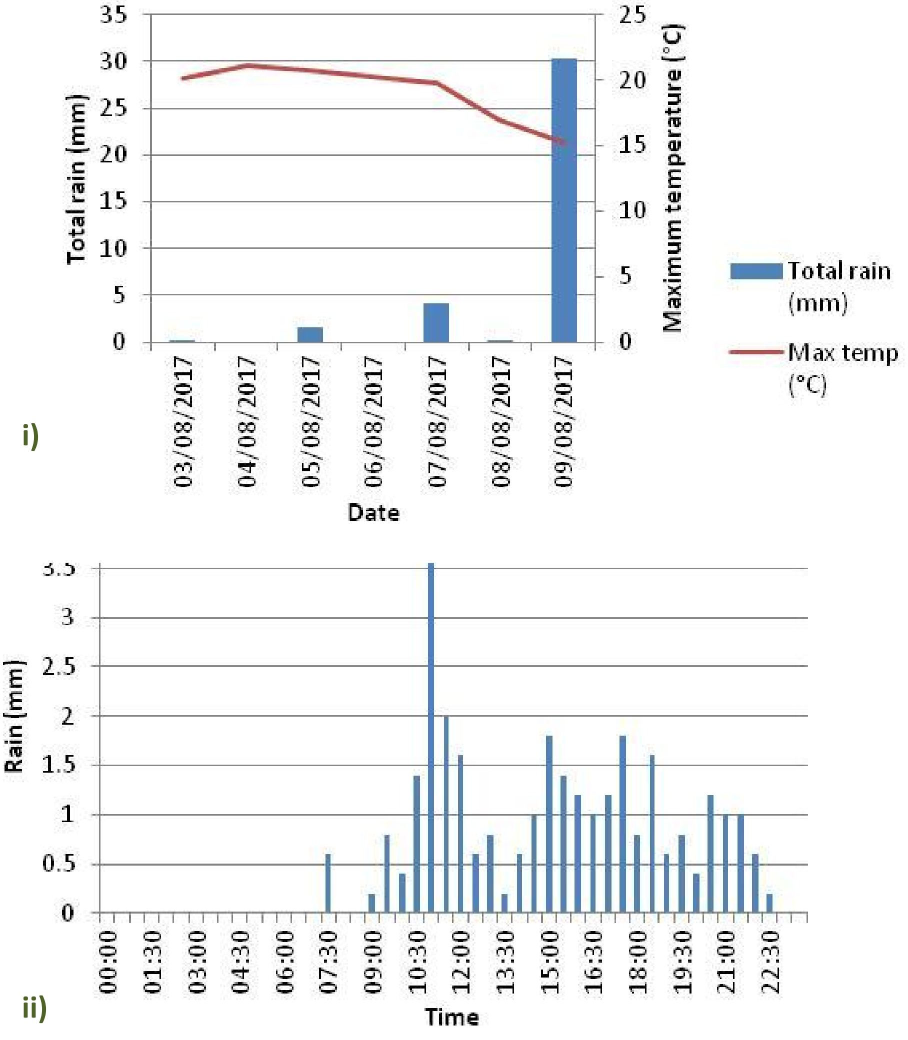


Figure 17. Details of rain event on the 9th August 2017 at Henrietta House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

Alexandra House swale (FPC1) performance during 30.4 mm rain event on 9th August 2017

A complete collection of the images from the Alexandra House swale during the rain event from 06:30 to 23:59 on the 9th August 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 10:40 during the peak of the rainfall, despite substantial input from the neighbouring roof, there was no obvious standing water within or around the rain garden (Figure 18.i). By the time of the end of the rain event at 23:54, there was also no obvious pooled water (Figure 18.ii) indicating that the swale was infiltrating all of the stormwater.

i)

Figure 18. (see below)

ii)

Figure 18. Time-lapse camera images from Alexandra House swale (FPC1), 09/05/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 10:40 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 23:55 on the same day.

Community Hall and Sofia House basins (FPC2) performance during 30.4 mm rain event on 9th August 2017

A complete collection of the images from the community hall and Sofia House basins during the rain event from 07:00 to 23:59 on the 9th August 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 10:48 during the peak of the rainfall, despite substantial input from the community hall roof, there was no obvious standing water within or around the basins (Figure 19.i). Following the cessation of the event at 23:59, there was also no obvious pooled water (Figure 19.ii) indicating that the basins were infiltrating all of the stormwater.

i)

ii)

Figure 19. Time-lapse camera images from Community Hall and Sofia House basins (FPC2), 09/08/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 10:48 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 23:59 on the same day.

Adella House grass and stoney basins (FPC3) performance during 30.4 mm rain event on 9th August 2017

A complete collection of the images from the Adella House basins during the rain event from 07:00 to 23:59 on the 9th August 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 10:30 during the peak of the rainfall, despite substantial input from the Adella House roof, there was no obvious standing water within or around the basins (Figure 20.i). Following the cessation of the event at 23:48, there was also no obvious pooled water (Figure 20.ii) indicating that the basins were infiltrating all of the stormwater.

i)

Figure 20. (see below)

ii)

Figure 20. Time-lapse camera images from Adella House grass and stoney basins (FPC3), 09/08/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 10:30 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 23:48 on the same day.

Beatrice House swale (FPC4) performance during 30.4 mm rain event on 9th August 2017

A complete collection of the images from Beatrice House swale during the rain event from 07:00 to 23:59 on the 9th August 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 10:36 during the peak of the rainfall, despite substantial input from the Beatrice House roof, there was no obvious standing water within or around the swale (Figure 21.i). Following the cessation of the event at 23:54, there was also no obvious pooled water (Figure 21.ii) indicating that the swale was infiltrating all of the stormwater.

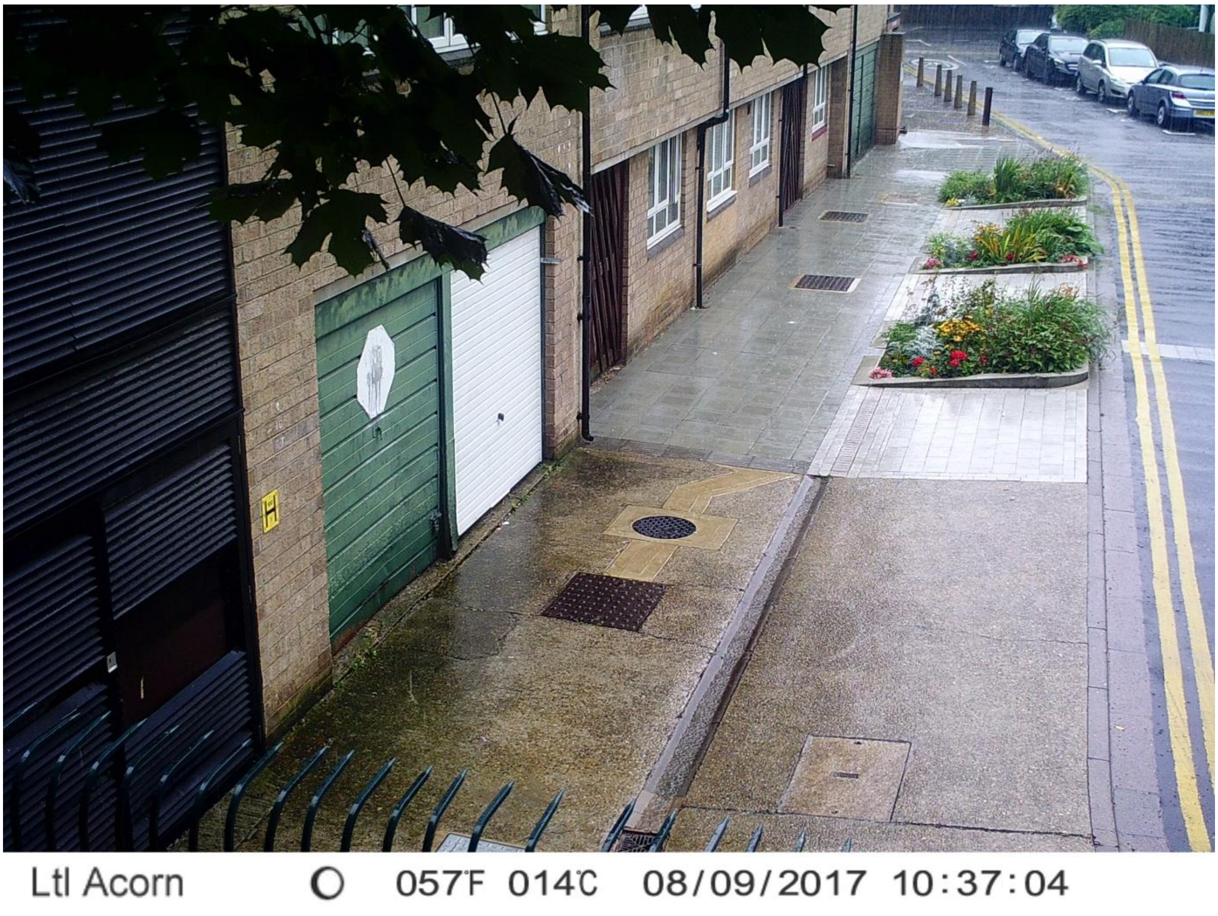
i)

ii)

Figure 21. Time-lapse camera images from Beatrice House swale (FPC4), 09/08/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 10:36 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 23:54 on the same day.

Cheeseman Terrace rain gardens (FPC6) performance during 30.4 mm rain event on 9th August 2017

A complete collection of the images from Cheeseman Terrace rain gardens during the rain event from 07:00 to 23:59 on the 9th August 2017 were captured and analysed. They demonstrated that the rain gardens were able to retain and attenuate all of the rainfall that fell directly onto the area. Due to the design of the underdrainage from the road, analysis of pressure sensor data is required in order to establish whether all of the runoff from the road was also managed. Nevertheless, the images also demonstrated that at around 10:37 during the peak of the rainfall, there was no obvious standing water within or around the rain gardens (Figure 22.i). Following the cessation of the event at 23:52, there was also no obvious pooled water (Figure 22. ii) indicating that the rain gardens were not becoming saturated with stormwater.



i)

Figure 22. (see below)

ii)

Figure 22. Time-lapse camera images from Cheeseman Terrace rain gardens (FPC6), 08/09/2011. Images show i) no evidence of overflowing during a period of high rain intensity at 10:37 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 23:52 on the same day.

Summer - Event 2

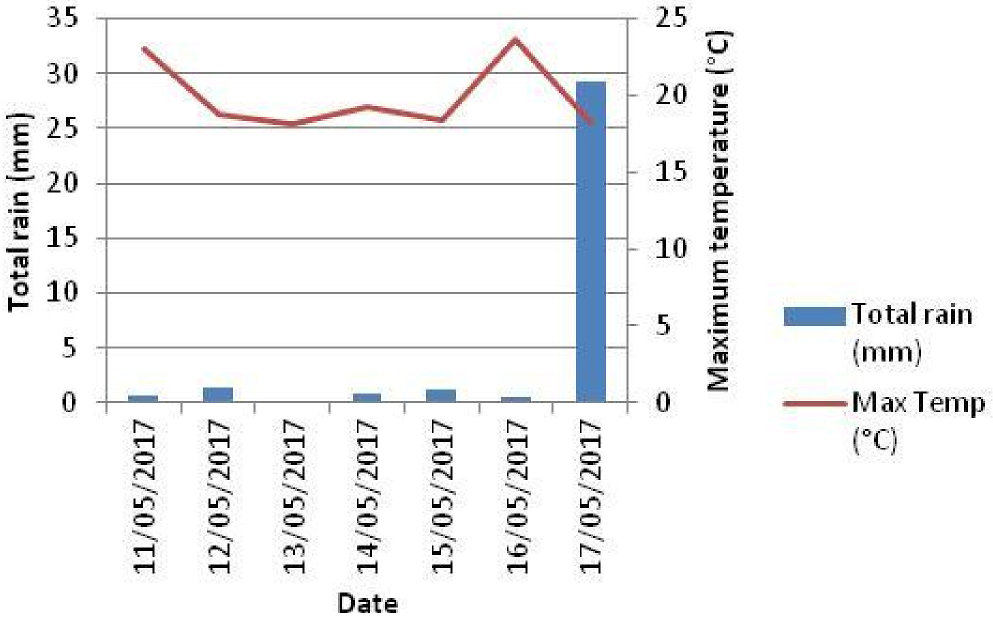
The next largest rain event in summer (defined as mm of rain per 24 hr period) was on the 17th May 2017. For this rain event, a total of 29.2 mm of rain was recorded falling at Henrietta House and at Richard Knight House.

At Richard Knight House, this was a rain event that consisted of three discrete events with the most intense period of rain in the morning. The weather preceding the event was damp with light rain every day (Figure 23). The highest volume and intensity of rainfall during this event fell between 03:30 and 04:30, with the highest rain volume of 6.2 mm in an hour and the highest rain rate recorded as 10.6 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

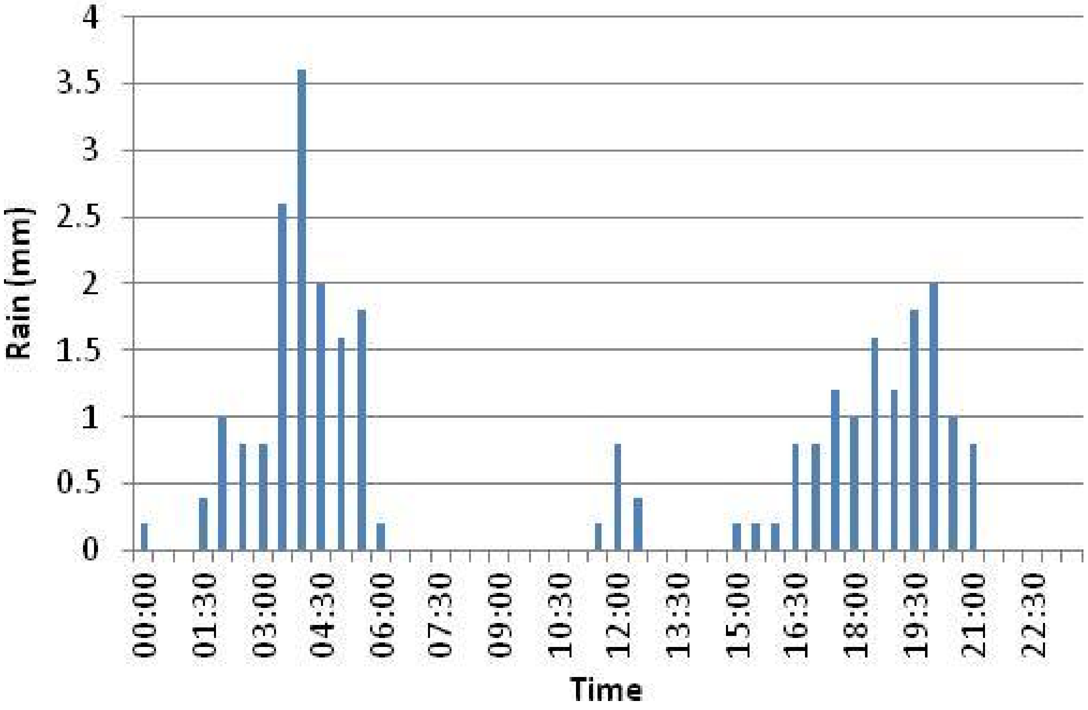
The time-lapse camera recorded the performance of the SuDS feature at Richard Knight House during this prolonged rain event on the 17th May 2017.

Richard Knight House rain garden (FPC4) performance during 38 mm rain event on 17th May 2017

A complete collection of the images from the Richard Knight House rain garden during the rain event from 00:30 to 21:00 on the 17th May 2017 were captured and analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 03:30 during the peak of the rainfall, despite substantial input from the neighbouring roofs, there was no obvious standing water around the rain garden (Figure 24.i). By the time of the end of the rain event at 21:15, there was also no obvious pooled water (Figure 24.ii) indicating that the rain garden was infiltrating all of the stormwater.



i)



ii)

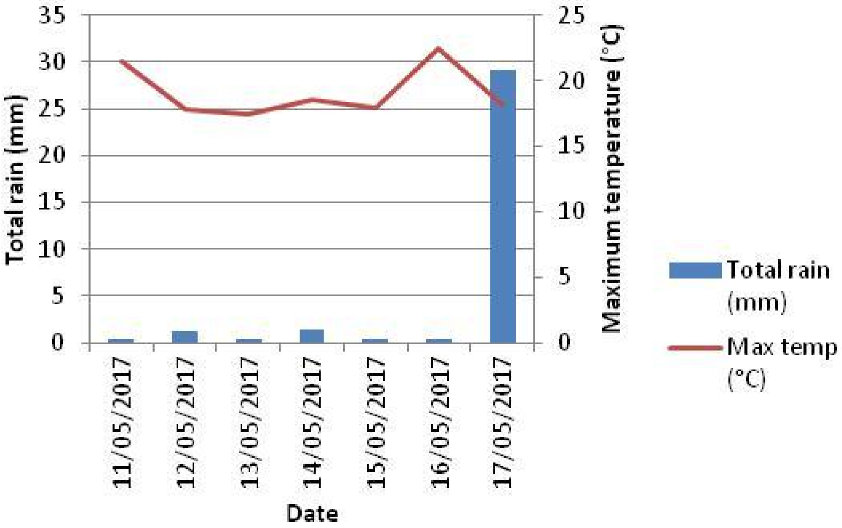
Figure 23. Details of rain event on the 17th May 2017 at Richard Knight House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes

Figure 24. Time-lapse camera images from Richard Knight House rain garden (FPC5), 17/05/2017. Images show i) no evidence of overflowing during period of highest rain intensity at 03:28 and ii) evidence of 100% infiltration/conveyance by the end of the rain event at 21:12 on the same day.

At Henrietta House, a similar pattern of a rain event occurred comprising three separate periods of rain, the most intense being in the early hours of the morning. The rain event was also preceded by several days of light rain (Figure 25). The highest volume and intensity of rainfall during this event fell between 03:30 and 04:30, with the highest rain volume of 5.2 mm in an hour and the highest rain rate recorded as 8.8 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse cameras at Queen Caroline Estate and Cheeseman Terrace recorded the performance of the SuDS features during this prolonged rain event on the 17th May 2017.

i)



ii)

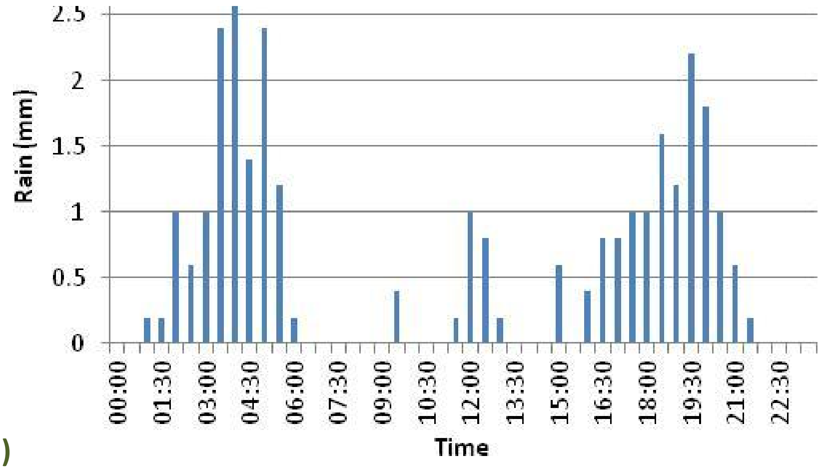


Figure 25. Details of rain event on the 17th May 2017 at Henrietta House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

Alexandra House swale (FPC1) performance during 30.4 mm rain event on 17th May 2017

A complete collection of the images from the Alexandra House swale during the rain event from 00:30 to 21:30 on the 17th May 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 03:25 during the peak of the rainfall, despite substantial input from the neighbouring roof, there was no obvious standing water within or around the rain garden (Figure 26.i). By the time of the end of the rain event at 21:10, there was also no obvious pooled water (Figure 26. ii) indicating that the swale was infiltrating all of the stormwater.

i)

Figure 26. (see below)

ii)

Figure 26. Time-lapse camera images from Alexandra House swale (FPC1), 17/05/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 03:25 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 21:10 on the same day.

Community Hall and Sofia House basins (FPC2) performance during 29.2 mm rain event on 17th May 2017

A complete collection of the images from the community hall and Sofia House basins during the rain event from 00:30 to 21:30 on the 17th May 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 03:30 during the peak of the rainfall, despite substantial input from the community hall roof, there was no obvious standing water within or around the basins (Figure 27.i). Following the cessation of the event at 21:25, there was also no obvious pooled water (Figure 27.ii) indicating that the basins were infiltrating all of the stormwater.

i)

ii)

Figure 27. Time-lapse camera images from Community Hall and Sofia House basins (FPC2), 17/05/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 03:32 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 21:25 on the same day.

Adella House grass and stoney basins (FPC3) performance during 29.2 mm rain event on 17th May 2017

A complete collection of the images from the Adella House basins during the rain event from 00:30 to 21:30 on the 17th May 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 03:30 during the peak of the rainfall, despite substantial input from the Adella House roof, there was no obvious standing water within or around the basins (Figure 28.i). Following the cessation of the event at 21:30, there was also no obvious pooled water (Figure 28.ii) indicating that the basins were infiltrating all of the stormwater.

i)

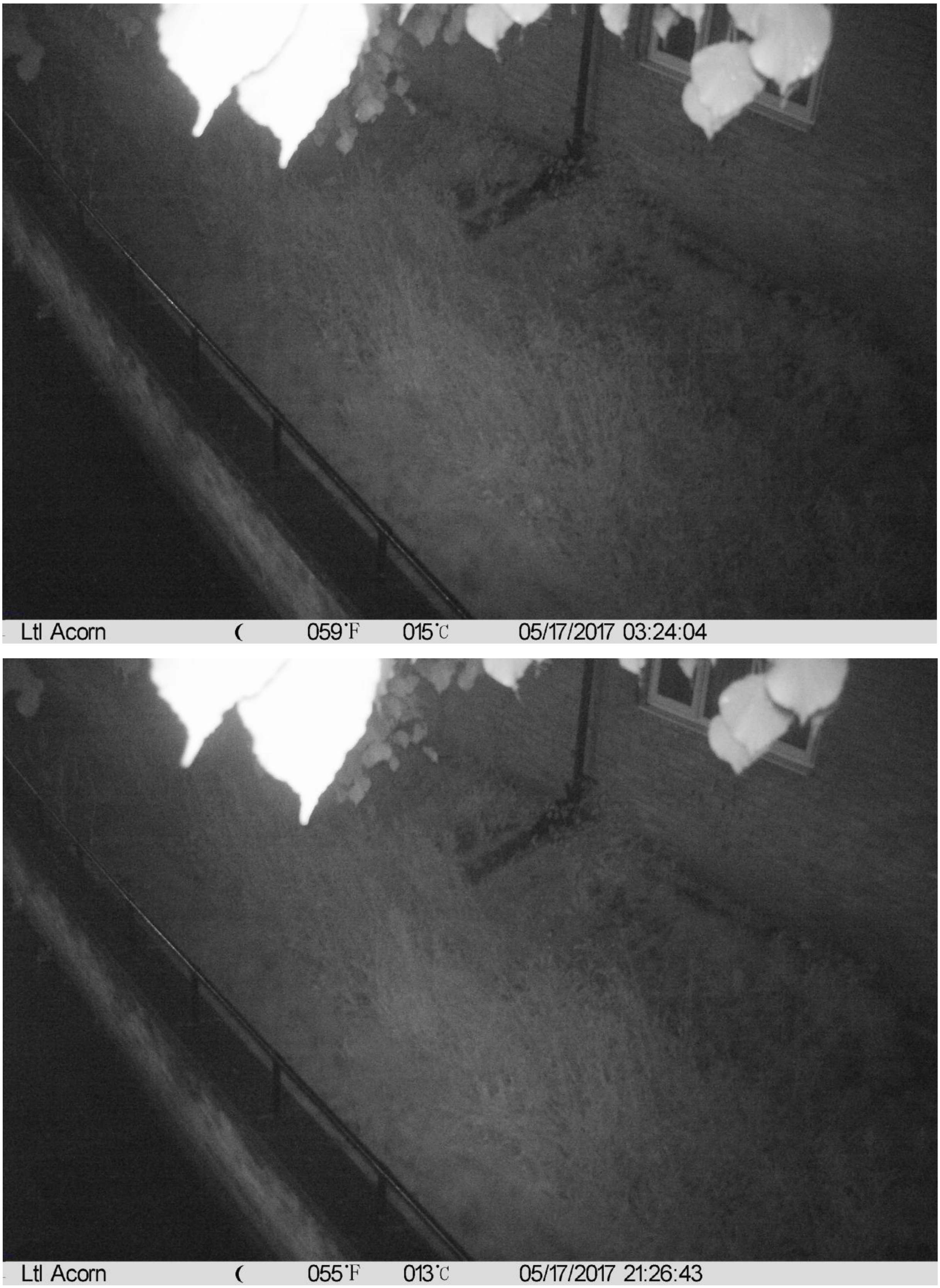
Figure 28. (see below)

ii)

Figure 28. Time-lapse camera images from Adella House grass and stoney basins (FPC3), 17/05/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 03:32 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 21:31 on the same day.

Beatrice House swale (FPC4) performance during 29.2 mm rain event on 17th May 2017

A complete collection of the images from Beatrice House swale during the rain event from 00:30 to 21:30 on the 17th May 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 03:24 during the peak of the rainfall, despite substantial input from the Beatrice House roof, there was no obvious standing water within or around the swale (Figure 29.i). Following the cessation of the event at 21:26, there was also no obvious pooled water (Figure 29.ii) indicating that the swale was infiltrating all of the stormwater.



i)

ii)

Figure 29. Time-lapse camera images from Beatrice House swale (FPC4), 17/05/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 03:24 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 21:26 on the same day.

Cheeseman Terrace rain gardens (FPC6) performance during 29.2 mm rain event on 17th May 2017

A complete collection of the images from Cheeseman Terrace rain gardens during the rain event from 00:30 to 21:30 on the 17th May 2017 were captured and analysed. They demonstrated that the rain gardens were able to retain and attenuate all of the rainfall that fell directly onto the area. Due to the design of the underdrainage from the road, analysis of pressure sensor data is required in order to establish whether all of the runoff from the road was also managed. Nevertheless, the images also demonstrated that at around 03:35 during the peak of the rainfall, there was no obvious standing water within or around the rain gardens (Figure 30.i). Following the cessation of the event at 21:20, there was also no obvious pooled water (Figure 30.ii) indicating that the rain gardens were not becoming saturated with stormwater.

i)

Figure 30. (see below)

ii)

Figure 30. Time-lapse camera images from Cheeseman Terrace rain gardens (FPC6), 17/05/2011. Images show i) no evidence of overflowing during a period of high rain intensity at 03:37 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 21:22 on the same day.

3.3 Flowmeter rainfall runoff monitoring

In addition to the time-lapse camera monitoring, more precise monitoring was carried out on a selection of the green infrastructure components implemented across the estates (Connop and Clough 2016; Connop et l. 2016). Components selected included the rain gardens at Cheeseman Terrace, and the pramshed green roofs and Beatrice swale at Queen Caroline Estate. Using installed flowmeters these SuDS components were monitored during this third monitoring period from October 2016 to September 2017.

Due to the continuous nature of the monitoring, substantial volumes of data were generated for all rain events. In order to present the most relevant of this data within this report, similarly to the time-lapse cameras, the five largest rain events during the winter and summer of this monitoring period are presented. The largest events were selected as they were those of most interest in terms of the potential to cause localised flooding and overload London's storm drain system.

Details of the five largest winter and summer rain events at Queen Caroline Estate are presented in Table 1. A large rain event was defined in terms of the total rainfall falling within the 24hr period of a day. Quantifying a large event in this way is inclusive of events of short duration with high intensity and events of more sustained but less intense rainfall. As such it provides a good snapshot of how the SuDS features perform under different rain event types.

For both the Queen Caroline Estate monitoring and the Cheeseman Terrace monitoring, the Henrietta House weather station was the closest rainfall monitoring location. As such, only data from this weather station was used for the analyses.

3.3.1.Cheeseman Terrace Monitoring

For the monitoring at Cheeseman Terrace, four pressure sensors were installed (Connop et al. 2016). These monitored the flow of stormwater from the roadside storm drains, through a series of three rain gardens and then to a controlled release flow chamber. The controlled release chamber was designed to release stormwater to the combined sewer system once the capacity of the rain gardens became overloaded. In terms of the pressure sensors (PS), the direction of flow would be expected to be PS2 --> PS3 --> PS4 --> PS5, with PS5 being the overflow to the combined sewer system (Figure 31). Pressure sensors 2 and 4 are positioned inside the underlying downpipes in inspection chambers and so are measuring the flow from the underdrains beneath the road. Pressure sensor 3 was positioned in the soil to measure soil saturation from direct rainfall and infiltration from the neighbouring gardens' underdrains.

Results are presented below.

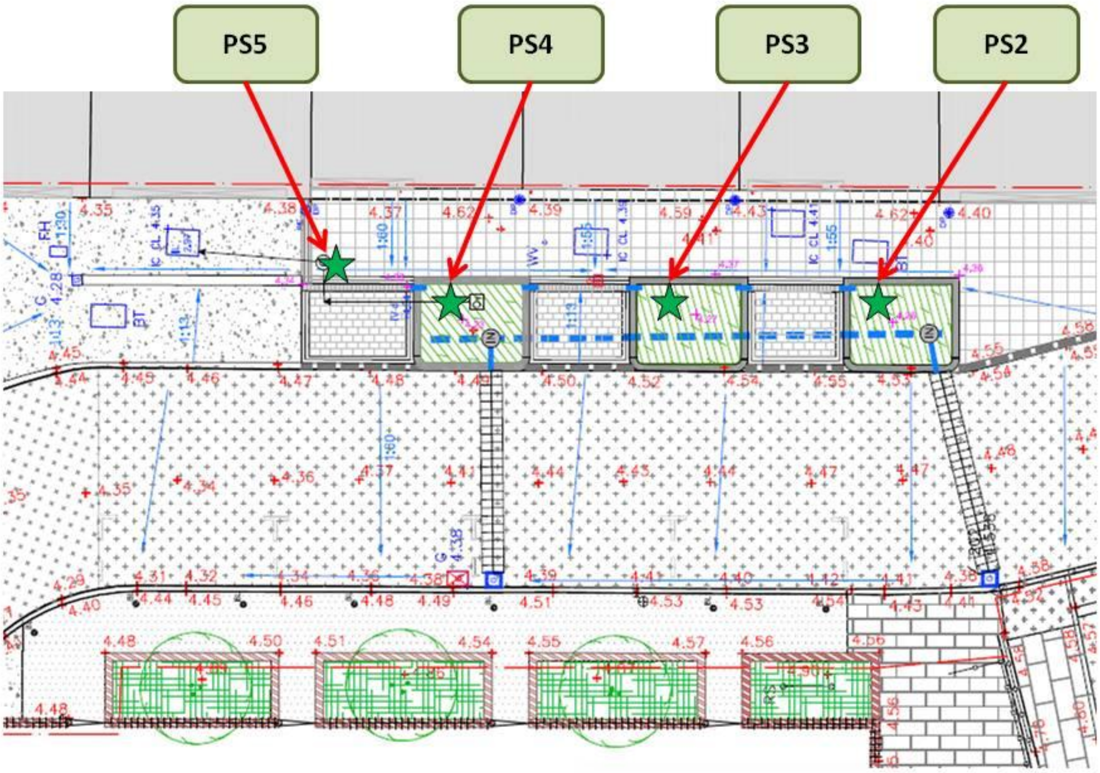
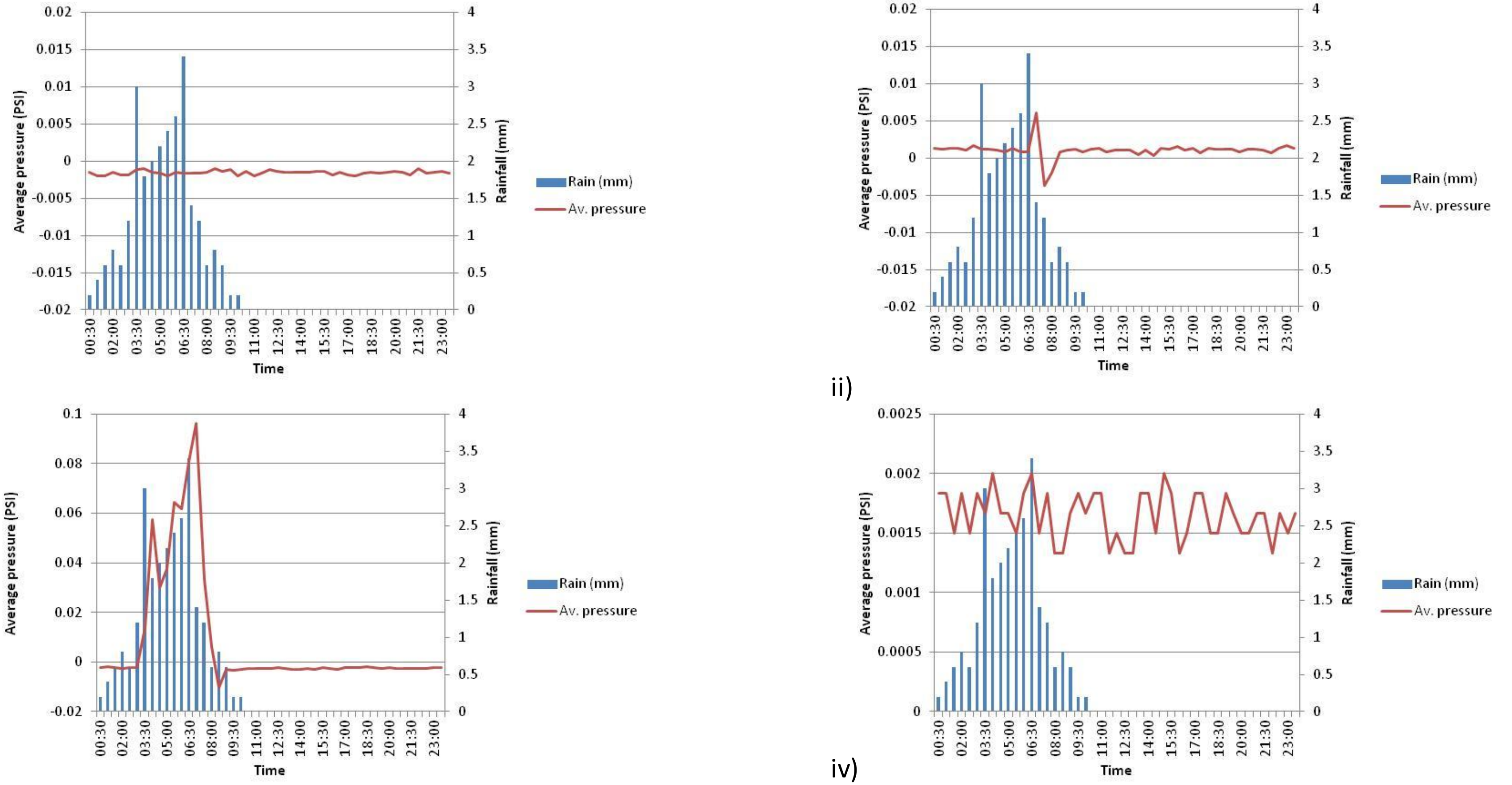


Figure 31. Plan of the Cheeseman Terrace rain gardens and monitoring equipment. PS represents the pressure sensors installed beneath each rain garden and the one installed in the control flow chamber.

Winter: 1 **Date:** 9th November 2016 **Rain event:** 26.4 mm **Maximum Intensity:** 12mm/hr **Temperature:** 9.1°C


i)

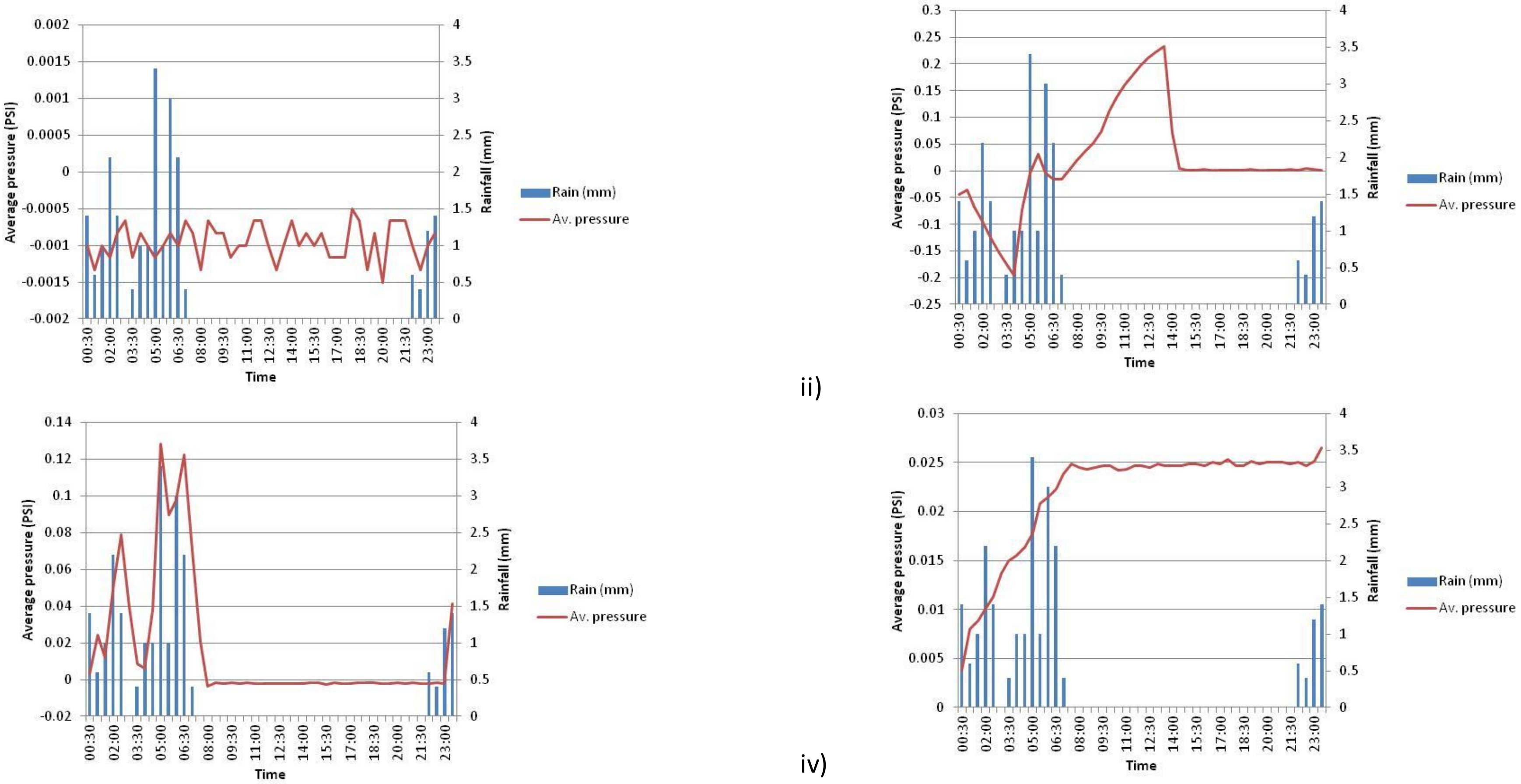
ii)

iii)

iv)

Figure 32. Cheeseman Terrace rain gardens monitoring 9th November 2016. Graphs show the records of pressure sensors positioned in i) first rain garden (PS2), ii) middle rain garden (PS3), iii) last rain garden (PS4) and iv) controlled release overflow chamber (PS5). Blue bars represent the pattern of rainfall, the red line indicates the pressure measured by the pressure sensor. Increase in pressure therefore corresponds with an increase in water level within chambers (PS 2, 4 and 5) or water saturation within the soil (PS3).

Winter: 2 **Date:** 20th November 2016 **Rain event:** 23.4 mm **Maximum Intensity:** 19.6 mm/hr **Temperature:** 8.8°C



i)

ii)

iii)

iv)

Figure 33. Cheeseman Terrace rain gardens monitoring 20th November 2016. Graphs show the records of pressure sensors positioned in i) first rain garden (PS2), ii) middle rain garden (PS3), iii) last rain garden (PS4) and iv) controlled release overflow chamber (PS5). Blue bars represent the pattern of rainfall, the red line indicates the pressure measured by the pressure sensor. Increase in pressure therefore corresponds with an increase in water level within chambers (PS 2, 4 and 5) or water saturation within the soil (PS3).

Winter: 3 **Date:** 12th January 2017 **Rain event:** 16 mm **Maximum Intensity:** 9.2 mm/hr **Temperature:** 6.8°C

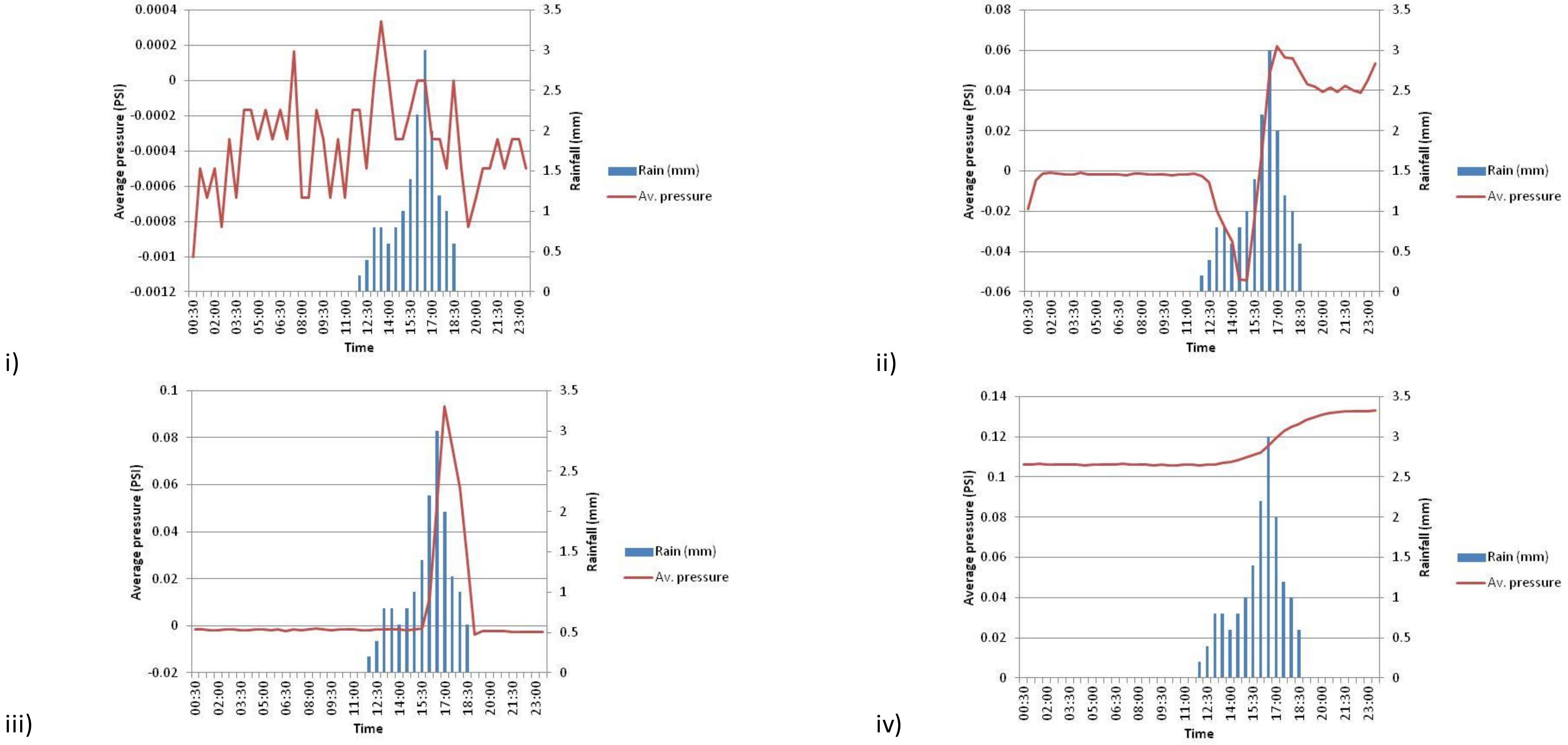
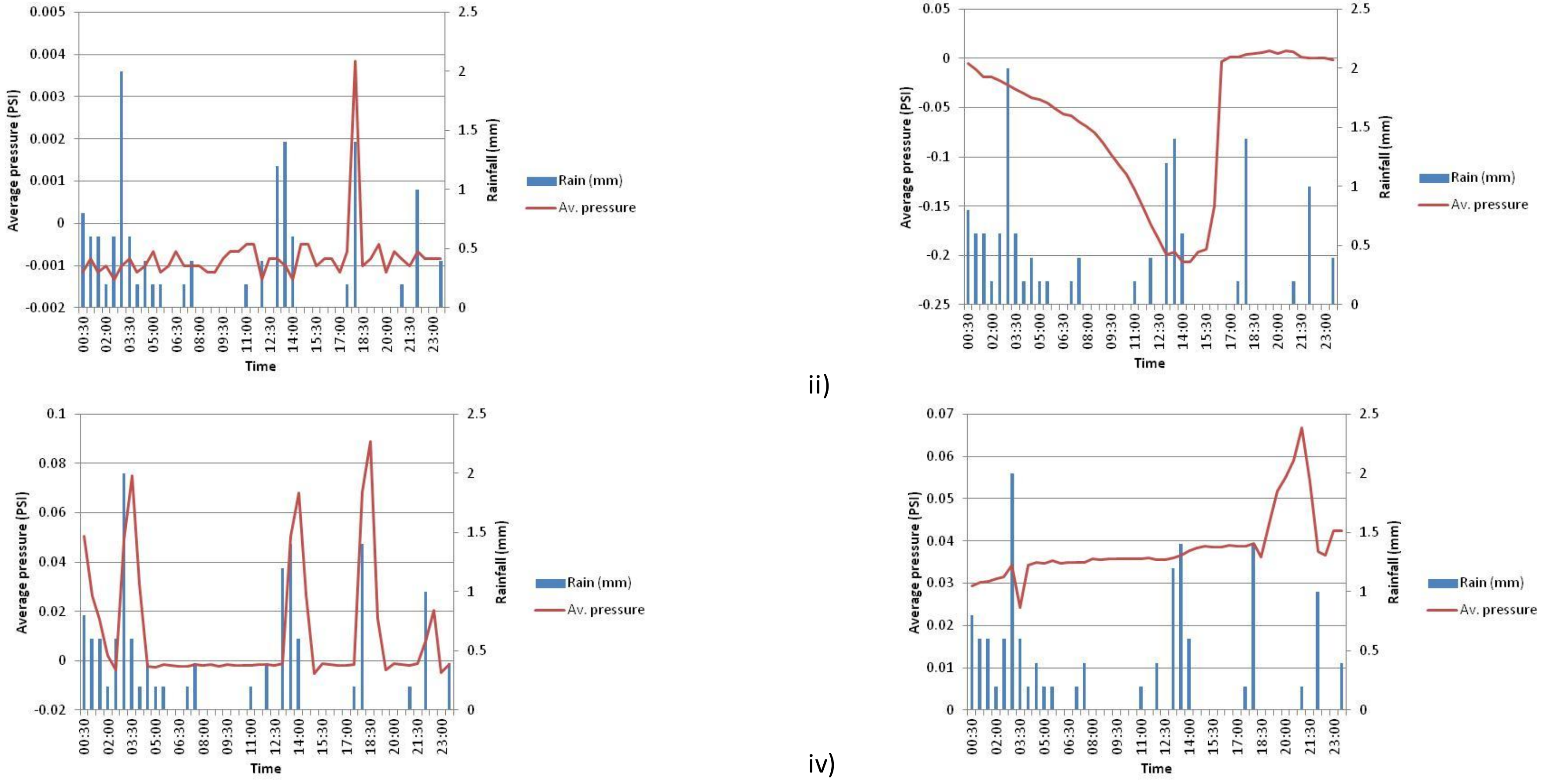


Figure 34. Cheeseman Terrace rain gardens monitoring 12th January 2017. Graphs show the records of pressure sensors positioned in i) first rain garden (PS2), ii) middle rain garden (PS3), iii) last rain garden (PS4) and iv) controlled release overflow chamber (PS5). Blue bars represent the pattern of rainfall, the red line indicates the pressure measured by the pressure sensor. Increase in pressure therefore corresponds with an increase in water level within chambers (PS 2, 4 and 5) or water saturation within the soil (PS3).

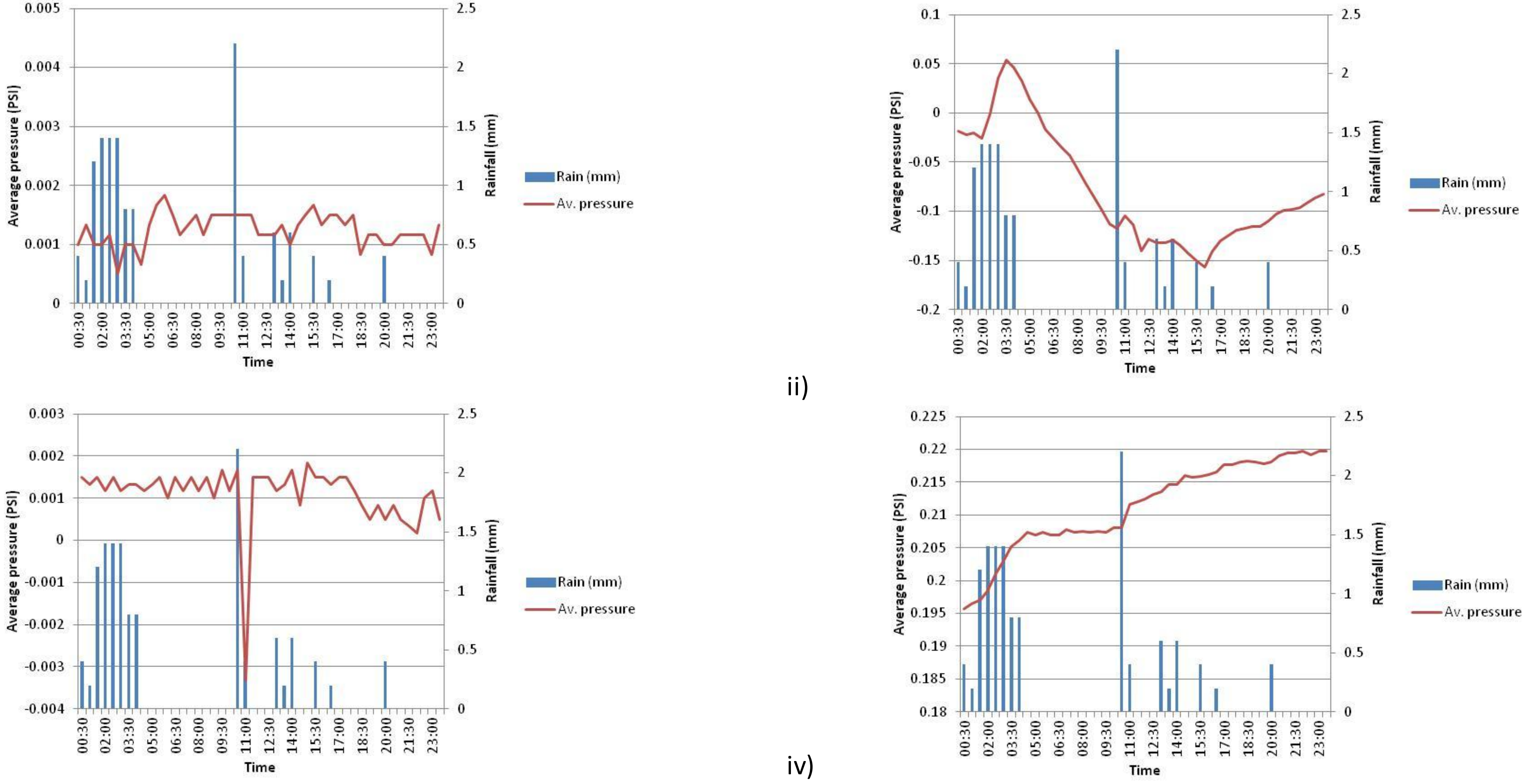
Winter: 4 **Date:** 21st November 2016 **Rain event:** 15 mm **Maximum Intensity:** 22.4 mm/hr **Temperature:** 12.8°C



i) ii) iii) iv)

Figure 35. Cheeseman Terrace rain gardens monitoring 21st November 2016. Graphs show the records of pressure sensors positioned in i) first rain garden (PS2), ii) middle rain garden (PS3), iii) last rain garden (PS4) and iv) controlled release overflow chamber (PS5). Blue bars represent the pattern of rainfall, the red line indicates the pressure measured by the pressure sensor. Increase in pressure therefore corresponds with an increase in water level within chambers (PS 2, 4 and 5) or water saturation within the soil (PS3).

Winter: 5 **Date:** 27th February 2017 **Rain event:** 12.8 mm **Maximum Intensity:** 32.2 mm/hr **Temperature:** 9.3°C



i) ii) iii) iv)

Figure 36. Cheeseman Terrace rain gardens monitoring 27th February 2017. Graphs show the records of pressure sensors positioned in i) first rain garden (PS2), ii) middle rain garden (PS3), iii) last rain garden (PS4) and iv) controlled release overflow chamber (PS5). Blue bars represent the pattern of rainfall, the red line indicates the pressure measured by the pressure sensor. Increase in pressure therefore corresponds with an increase in water level within chambers (PS 2, 4 and 5) or water saturation within the soil (PS3).

Winter events summary

Winter event 1 - PS2 recorded no evidence of a change in water depth during or after the rainfall event. This indicated that all of the rainfall entering this first underdrain was either conveyed to the next rain garden or infiltrated into the substrate within and beneath this first rain garden. PS3 recorded a slight increase in soil saturation but this dropped rapidly and returned to the pre-rain event level very soon after the raised readings. PS4 reacted to the rain event with water level increasing. This is to be expected as this third rain garden would be expected to receive the majority of the rainfall that falls within the catchment area of this SuDS feature. Levels in PS4 returned to the pre-rainfall levels almost immediately after the cessation of the heaviest period of rainfall. PS5 (the overflow) showed no reaction to this rain event, indicating that the rain gardens were able to infiltrate all of the rainfall from the catchment.

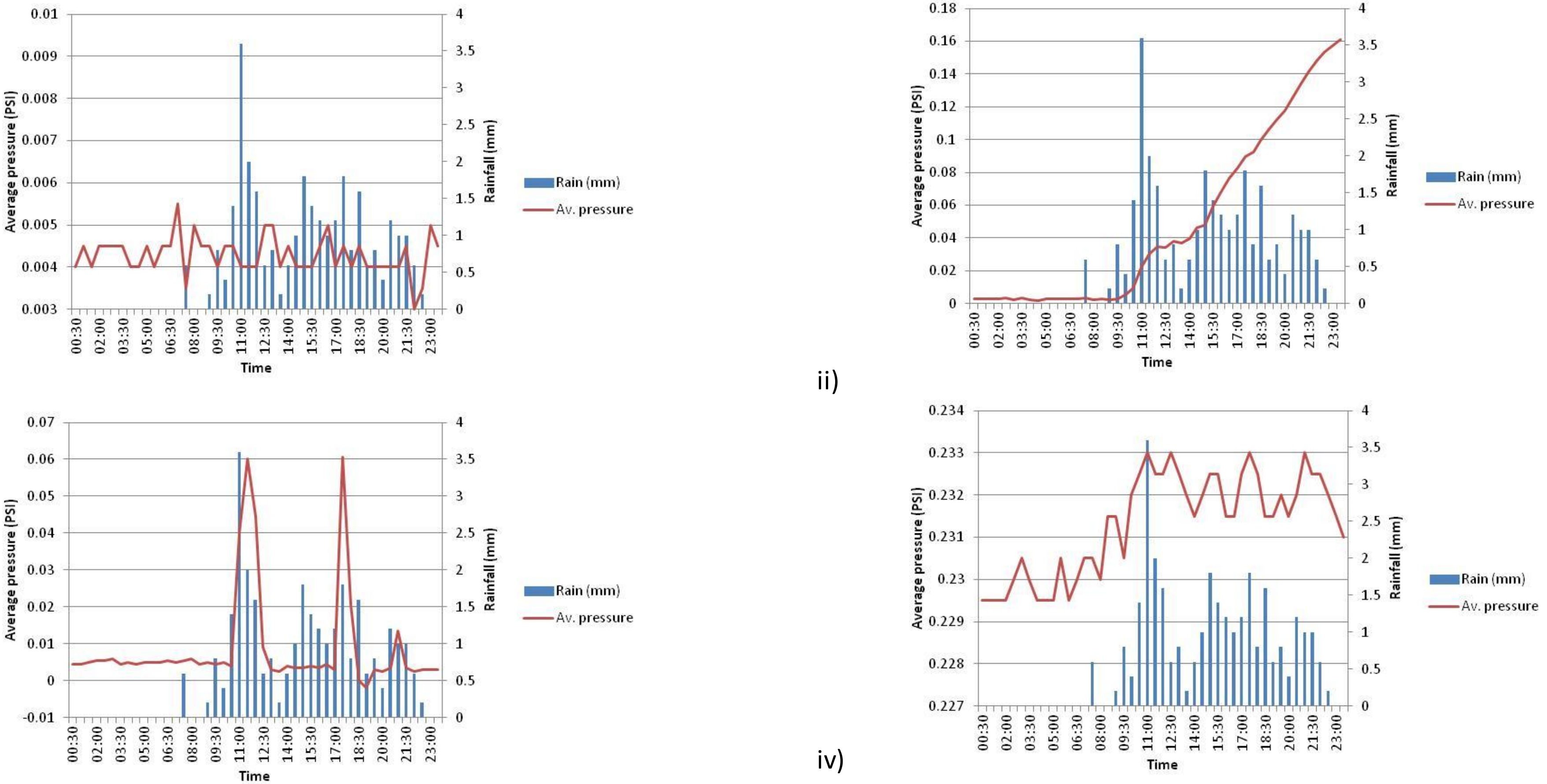
Winter event 2 - PS2 recorded no evidence of a change in water depth during or after the rainfall event. This indicated that all of the rainfall entering this first underdrain was either conveyed to the next rain garden or infiltrated into the substrate within and beneath this first rain garden. PS3 recorded an increase in soil saturation. This increase continued after the cessation of the rain event but declined once the daily temperature increase, presumably corresponding with soil drying. PS4 reacted to the rain event with water level increasing. This is to be expected as this third rain garden would be expected to receive the majority of the rainfall that falls within the catchement area of this SuDS feature. Levels in PS4 returned to the pre-rainfall levels almost immediately after the cessation of the heaviest period of rainfall. PS5 (the overflow) showed an increase in pressure during the rain event. This level did not drop, following the cessation of the rain event. This indicated that, whilst water was entering the overflow chamber, it was not reaching a level that would release it into the storm sewer. It is possible, therefore, that this storm water entered from the drain cover (which became cracked during the duration of the monitoring), rather than from the rain gardens.

Winter event 3 - PS2 recorded no evidence of a change in water depth during or after the rainfall event. This indicated that all of the rainfall entering this first underdrain was either conveyed to the next rain garden or infiltrated into the substrate within and beneath this first rain garden. PS3 recorded a drop then increase in soil saturation during the rain event. This increased level stayed constant following the cessation of the rain event, this indicated that the soil was not drying substantially following the rain event. PS4 reacted to the rain event with water level increasing. This is to be expected as this third rain garden would be expected to receive the majority of the rainfall that falls within the catchment area of this SuDS feature. Levels in PS4 returned to the pre-rainfall levels almost immediately after the cessation of the heaviest period of rainfall. PS5 (the overflow) showed a slight increase in pressure following the rain event. The level remained raised following the cessation of the rain event, indicating that it was not reaching a level that would release it into the storm sewer.

Winter event 4 - during the rain periods early in the day, PS2 recorded no evidence of a change in water depth during or after the rainfall event. This indicated that all of the rainfall entering this first underdrain was either conveyed to the next rain garden or infiltrated into the substrate within and beneath this first rain garden. However later, during the peak rainfall intensity, PS2 did record an increase in pressure. This increase declined again immediately following the cessation of the rain spell indicating again that all of the rainfall entering this first underdrain was either conveyed to the next rain garden or infiltrated into the substrate within and beneath this first rain garden. During the next spell, no increase in pressure was recorded. This indicated that sufficient infiltration had occurred for there to be capacity for new storage/infiltration by the time of this next rain period. The PS3 readings were unusual, dropping throughout the day (possibly due to a drying substrate) then increasing again following the more intense rainfall later in the day. Again PS4 was recorded reacting to the rain event with water level increasing during each rain spell of the 24hr event. Levels in PS4 returned to the pre-rainfall levels almost immediately after the cessation of the heaviest period of rainfall. PS5 (the overflow) showed an increase in pressure following the most intense period of the rain event. The level dropped soon after, indicating that the water level may have increased to such a level that control release to the storm sewer occurred.

Winter event 5 - PS2 recorded no evidence of a change in water depth during or after the rainfall event. This indicated that all of the rainfall entering this first underdrain was either conveyed to the next rain garden or infiltrated into the substrate within and beneath this first rain garden. The PS3 recorded an increase during the first spell of rain but then dropped steadily throughout the day (possibly due to a drying substrate) with only slight rises in pressure following subsequent rain spells. Apart from an unusual drop in pressure corresponding with a rain spell, PS4 recorded no obvious reactions to the rain event throughout the day. This indicated that all of the rainfall entering this third rain garden underdrain infiltrated into the substrate within and beneath this first rain garden. PS5 (the overflow) showed a steady increase in pressure following the most intense period of the rain event. The level remained raised following the cessation of the rain event, indicating that it was not reaching a level that would release it into the storm sewer.

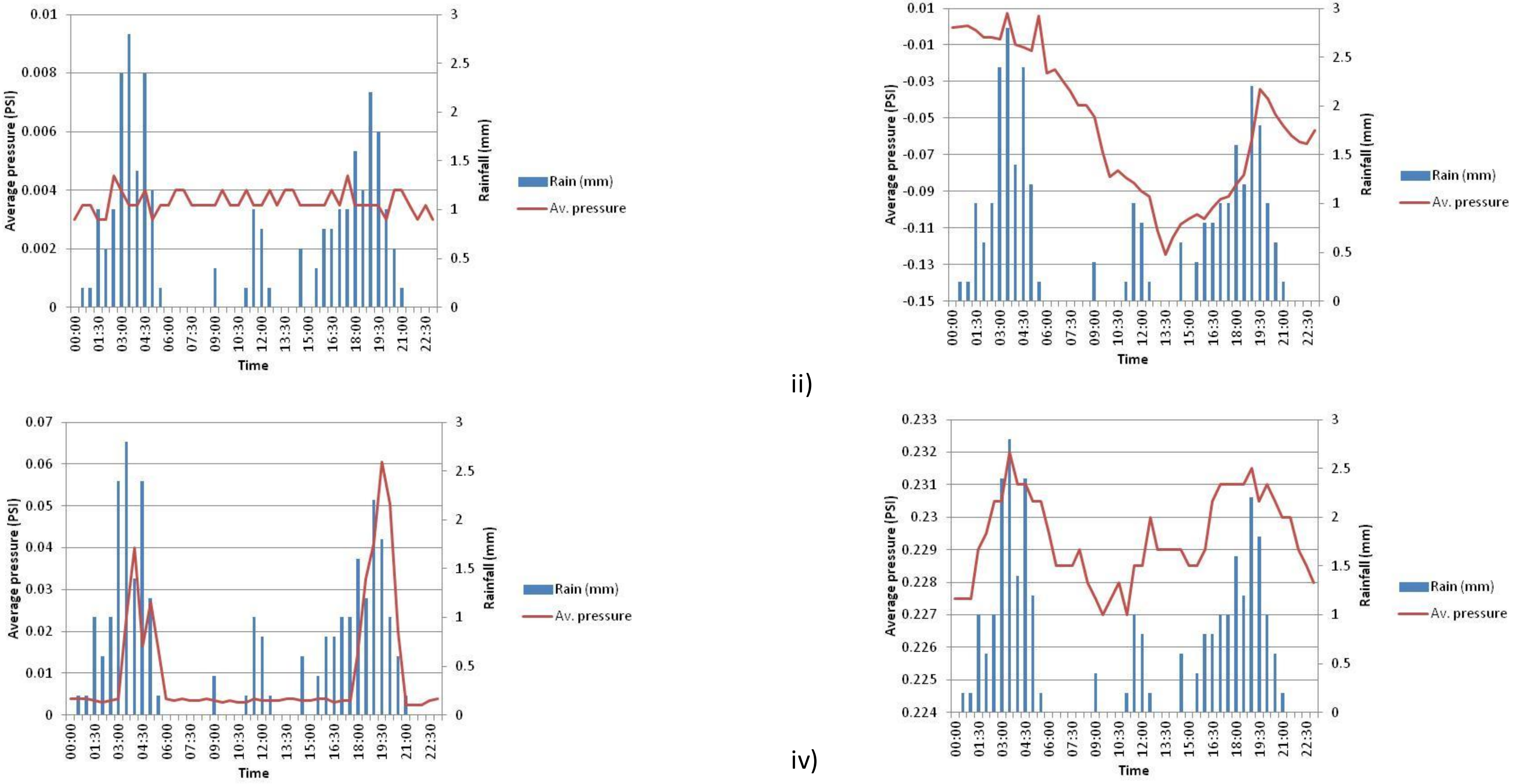
Summary: 1 **Date:** 9th August 2017 **Rain event:** 30.4 mm **Maximum Intensity:** 22.4 mm/hr **Temperature:** 15.3°C



i) ii) iii) iv)

Figure 37. Cheeseman Terrace rain gardens monitoring 9th August 2017. Graphs show the records of pressure sensors positioned in i) first rain garden (PS2), ii) middle rain garden (PS3), iii) last rain garden (PS4) and iv) controlled release overflow chamber (PS5). Blue bars represent the pattern of rainfall, the red line indicates the pressure measured by the pressure sensor. Increase in pressure therefore corresponds with an increase in water level within chambers (PS 2, 4 and 5) or water saturation within the soil (PS3).

Summary: 2 **Date:** 17th May 2017 **Rain event:** 29.2 mm **Maximum Intensity:** 8.8 mm/hr **Temperature:** 18.2°C



i)

ii)

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Figure 38. Cheeseman Terrace rain gardens monitoring 17th May 2017. Graphs show the records of pressure sensors positioned in i) first rain garden (PS2), ii) middle rain garden (PS3), iii) last rain garden (PS4) and iv) controlled release overflow chamber (PS5). Blue bars represent the pattern of rainfall, the red line indicates the pressure measured by the pressure sensor. Increase in pressure therefore corresponds with an increase in water level within chambers (PS 2, 4 and 5) or water saturation within the soil (PS3).

Summer: 3 **Date:** 30th July 2017 **Rain event:** 20 mm **Maximum Intensity:** 69 mm/hr **Temperature:** 19.8°C

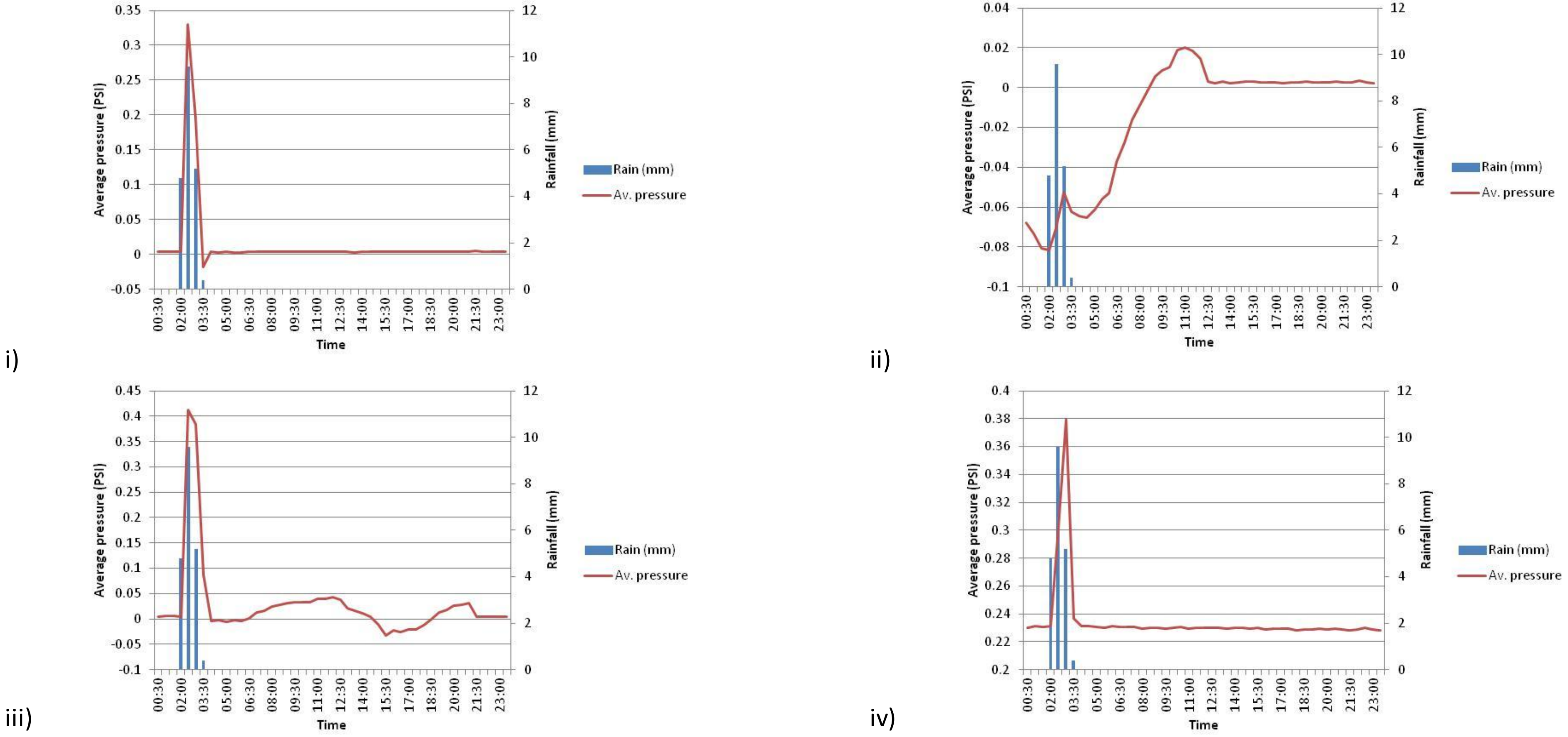
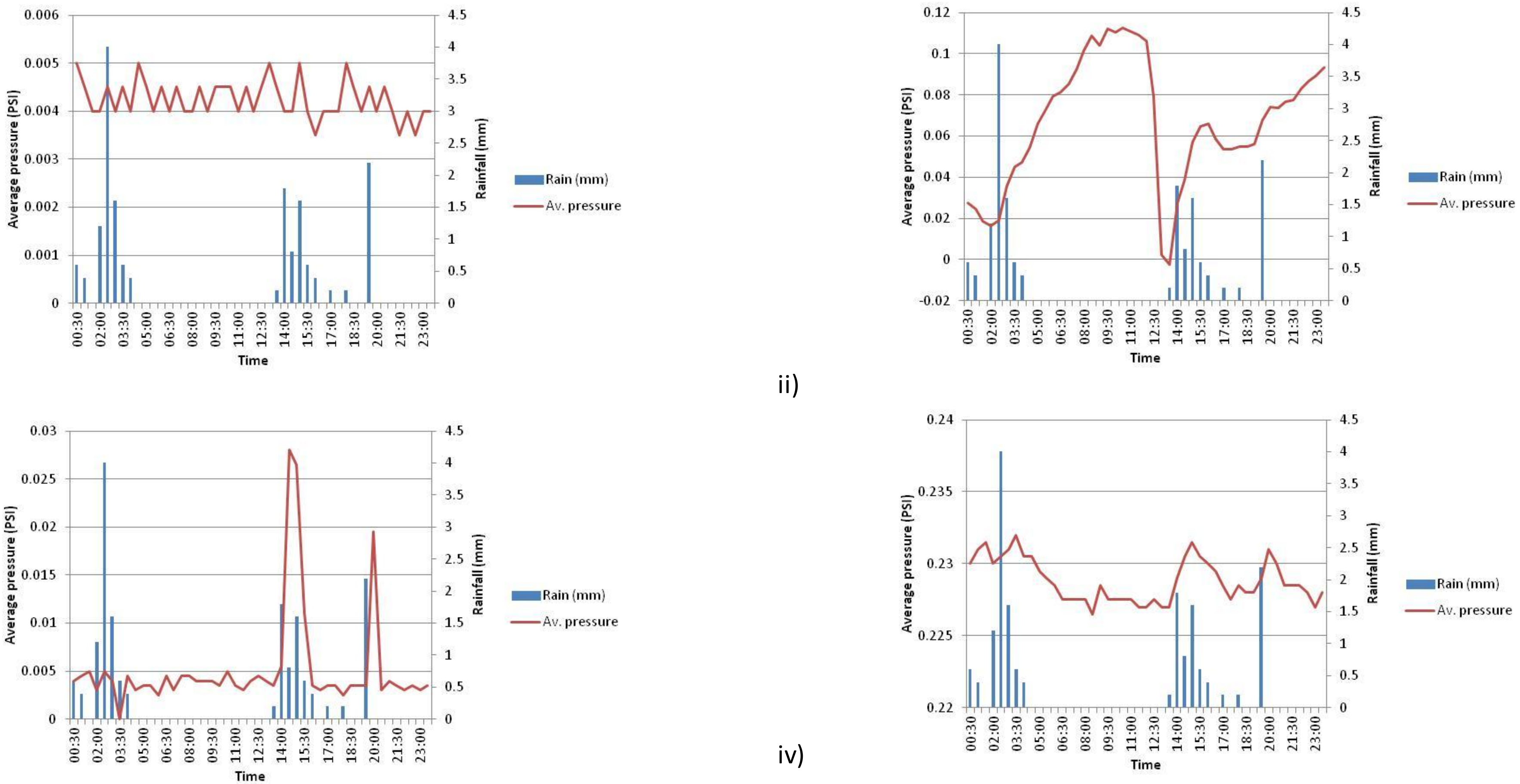


Figure 39. Cheeseman Terrace rain gardens monitoring 30th July 2017. Graphs show the records of pressure sensors positioned in i) first rain garden (PS2), ii) middle rain garden (PS3), iii) last rain garden (PS4) and iv) Controlled release overflow chamber (PS5). Blue bars represent the pattern of rainfall, the red line indicates the pressure measured by the pressure sensor. Increase in pressure therefore corresponds with an increase in water level within chambers (PS 2, 4 and 5) or water saturation within the soil (PS3).

Summer: 4 **Date:** 22nd July 2017 **Rain event:** 17.4 mm **Maximum Intensity:** 46.8 mm/hr **Temperature:** 18.9°C



i)

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Figure 40. Cheeseman Terrace rain gardens monitoring 22nd July 2017. Graphs show the records of pressure sensors positioned in i) first rain garden (PS2), ii) middle rain garden (PS3), iii) last rain garden (PS4) and iv) controlled release overflow chamber (PS5). Blue bars represent the pattern of rainfall, the red line indicates the pressure measured by the pressure sensor. Increase in pressure therefore corresponds with an increase in water level within chambers (PS 2, 4 and 5) or water saturation within the soil (PS3).

Summary: 5 **Date:** 11th/12th July 2017 **Rain event:** 31 mm **Maximum Intensity:** 19.8 mm/hr **Temperature:** 22.6°C

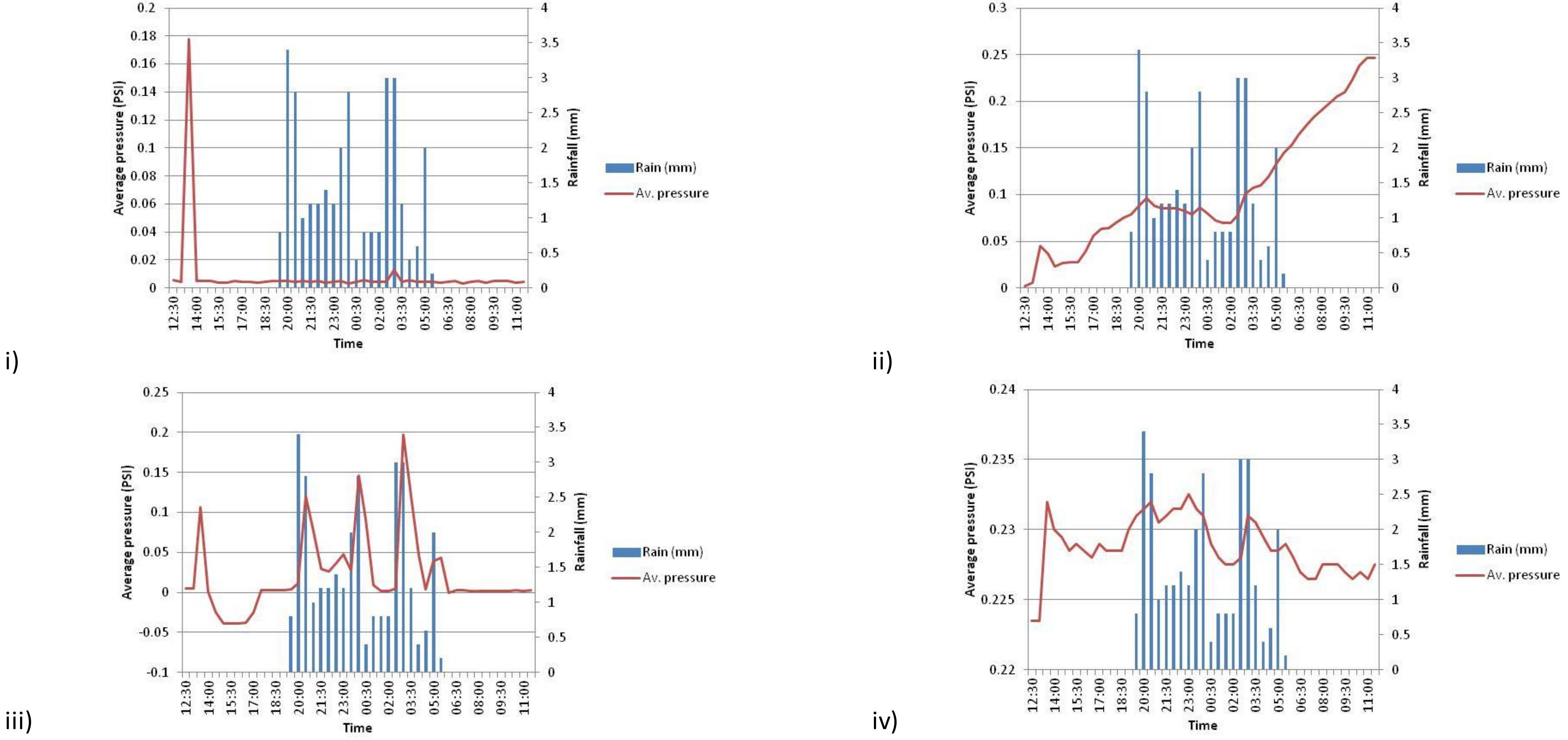

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Figure 41. Cheeseman Terrace rain gardens monitoring 11th/12th July 2017. Graphs show the records of pressure sensors positioned in i) first rain garden (PS2), ii) middle rain garden (PS3), iii) last rain garden (PS4) and iv) controlled release overflow chamber (PS5). Blue bars represent the pattern of rainfall, the red line indicates the pressure measured by the pressure sensor. Increase in pressure therefore corresponds with an increase in water level within chambers (PS 2, 4 and 5) or water saturation within the soil (PS3).

Summer events summary

Summer event 1 - PS2 recorded no evidence of a change in water depth during or after the rainfall event. This indicated that all of the rainfall entering this first underdrain was either conveyed to the next rain garden or infiltrated into the substrate within and beneath this first rain garden. PS3 recorded an increase in soil saturation. This did not drop immediately following the end of the rain event. PS4 reacted to the two highest intensity periods of rainfall during the rain event indicating an increase in water level in the underdrain. This is to be expected as this third rain garden would be expected to receive the majority of the rainfall that falls within the catchment area of this SuDS feature. Levels in PS4 returned to the pre-rainfall levels almost immediately after the cessation of the heaviest period of rainfall indicating that infiltration was occurring. PS5 (the overflow) showed a slight increase in pressure during the rain event corresponding with the peak intensities. The level dropped again following these rain periods. This indicated that some rainfall was reaching the overflow chamber and, either being released by the control flow, or evaporating between rain events.

Summer event 2 - PS2 recorded no evidence of a change in water depth during or after the rainfall event. This indicated that all of the rainfall entering this first underdrain was either conveyed to the next rain garden or infiltrated into the substrate within and beneath this first rain garden. PS3 recorded an increase in soil saturation during peak rain intensities, and a drop during that day in between these periods of high rain intensity. This indicated that the soil was drying out through evaporation/infiltrating between rain periods. PS4 reacted to the three highest intensity periods of rainfall during the rain event indicating an increase in water level in the underdrain. This is to be expected as this third rain garden would be expected to receive the majority of the rainfall that falls within the catchment area of this SuDS feature. Levels in PS4 returned to the pre-rainfall levels almost immediately after the cessation of the heaviest period of rainfall indicating that infiltration was occurring. PS5 (the overflow) showed an increase in pressure during the two highest intensity periods of the rain event. The level dropped again following these rain periods. This indicated that some rainfall was reaching the overflow chamber and, either being released by the control flow, or evaporating between rain events.

Summer event 3 - PS2 reacted during the rainfall event with an increase in pressure. This indicated an increase in water level. The level dropped immediately following the event indicating that all of the rainfall entering this first underdrain was either conveyed to the next rain garden or infiltrated into the substrate within and beneath this first rain garden. PS3 recorded an increase in soil saturation during and following the rain event. This eventually levelled out but did not decline, presumably due to the temperature dropping at night, thus reducing evaporation. PS4 reacted to the rain event indicating an increase in water level in the underdrain. Levels in PS4 returned to the pre-rainfall levels almost immediately after the cessation of the heaviest period of rainfall indicating that infiltration was occurring. PS5 (the overflow) showed an increase in pressure during the rain event. The level dropped rapidly following the cessation of the rain period. This indicated that some rainfall was reaching the overflow chamber and being released by the control flow following the end of the rain event.

Summer event 4 - PS2 recorded no evidence of a change in water depth during or after the rainfall event. This indicated that all of the rainfall entering this first underdrain was either conveyed to the next rain garden or infiltrated into the substrate within and beneath this first rain garden. PS3 recorded an increase in soil saturation during and following the first rain period of the rain event. This eventually declined, but increased again following the later rain period. PS4 recorded no increase in pressure during the first rain period of the rain event. However, during the later periods of rain, the pressure sensor recorded increases in pressure corresponding with an increase in water level in the underdrain. Levels in PS4 returned to the pre-rainfall levels almost immediately after the cessation of these periods of rain indicating that infiltration was occurring. PS5 (the overflow) showed slight increases in pressure during each period of rain. The level dropped following the cessation of the each period of rain. This indicated that some rainfall was reaching the overflow chamber and, either being released by the control flow, or evaporating following the end of the rain event.

Summer event 5 - PS2 recorded no evidence of a change in water depth during or after the rainfall event. This indicated that all of the rainfall entering this first underdrain was either conveyed to the next rain garden or infiltrated into the substrate within and beneath this first rain garden. There was a reaction to rainfall earlier in the day though that did not correspond with recorded rainfall. This was recorded on all sensors, so could have been a localised shower that occurred at Cheeseman Terrace but not where the weather station was positioned at Henrietta House. PS3 recorded an increase in soil saturation following the rain event. This did not decline, presumably due to a lack of evaporation at night. PS4 recorded an increase in pressure corresponding with each of the highest periods of rainfall intensity and the early period that was not recorded by the rain gauge. After the cessation of each period of rain, the pressure returned to the pre-rainfall levels almost immediately indicating that infiltration was occurring. PS5 (the overflow) showed slight increases in pressure during each period of rain. The level dropped following the cessation of the each period of rain. This indicated that some rainfall was reaching the overflow chamber and, either being released by the control flow, or evaporating following the end of the rain event.

Overall summary

The Cheeseman Terrace rain gardens appeared to be performing as designed. Gauges in the underdrains provided evidence that water levels increased during rain events but decreased rapidly following the cessation of the rainfall. The gauge in the soil of the middle garden recorded increases in soil saturation gradually during and following rain events. This was presumably due to the slow percolation of stormwater into the rain garden during and following the rain event. There was some evidence to indicate that stormwater was entering the control release chamber during some of the largest events, and thus that the capacity of the gardens was occasionally exceeded. It is impossible to prove how much of this was being fed from the rain garden system and how much was coming from the drain cover (due to its poor fit and damage sustained during the monitoring period). However, all water entering this chamber appeared to be released either by the slow release system, or by evaporation. As such the SuDS feature was performing as designed.

3.3.2.Queen Caroline Estate Monitoring

For the monitoring at Queen Caroline Estate, five v-notch weirs and one pressure sensor (at the base of Beatrice House swale) were installed (Connop and Clough 2016; Connop et al. 2016). The v-notch weirs monitored the flow of stormwater from three pram shed green roof downpipes (in front of Alexandra, Charlotte and Mary Houses) and from two downpipes from a control (non-greened) roof on Beatrice House. The pressure sensor measured water pressure within the Beatrice House swale. *N.B. It must be noted that v-notch weirs are less precise at low flow rates, so run off at low flow rates over long time periods from the roofs may be inaccurate. However, high flow rates would have a greater degree of accuracy and these are the rates of most importance related to storm drain overload.*

In order to assess the performance of the green infrastructure features, two different analyses were carried out for each of the rain events. The first was an analysis of the proportion of the total rainfall that was attenuated by each of the pram shed green roofs. The second was a graphical representation of the timing and intensity of runoff from the green roofs, control roofs and the values from the pressure sensor at the base of Beatrice House swale. Results are presented below.

Winter event 1 - 9th November 2016

Figure 42 shows the prevailing weather patterns preceding the rain event on the 9th November 2016.

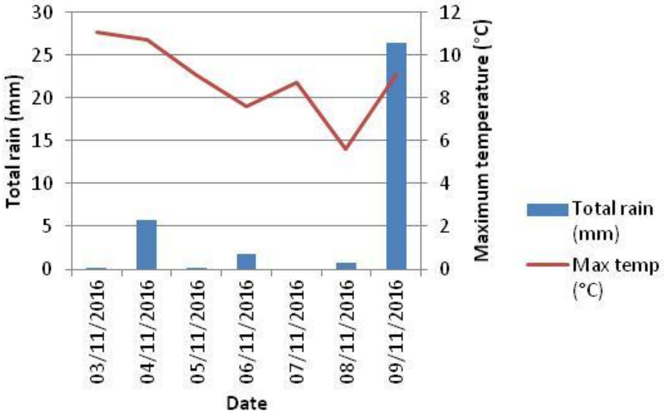


Figure 42. Prevailing weather conditions preceding one of the five largest rain events during the winter monitoring period at Queen Caroline Estate, Hammersmith. Rain event was 26.4 mm on 9th November 2016.

Table 3 contains the attenuation performance of the pramshed roofs during the rain event on the 9th November 2016.

Table 3. Pramshed green roof water attenuation performance during a rain event on the 9th November 2016. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	**Total rain (mm)**	**Catchment area (m)**	**Volume of rainfall in catchment area (L)**	**Attenuation (%)**
Alexandra	26.4	22	580.8	97
Charlotte	26.4	32	844.8	99
Mary	26.4	33.25	877.8	93
Average				**96.3**

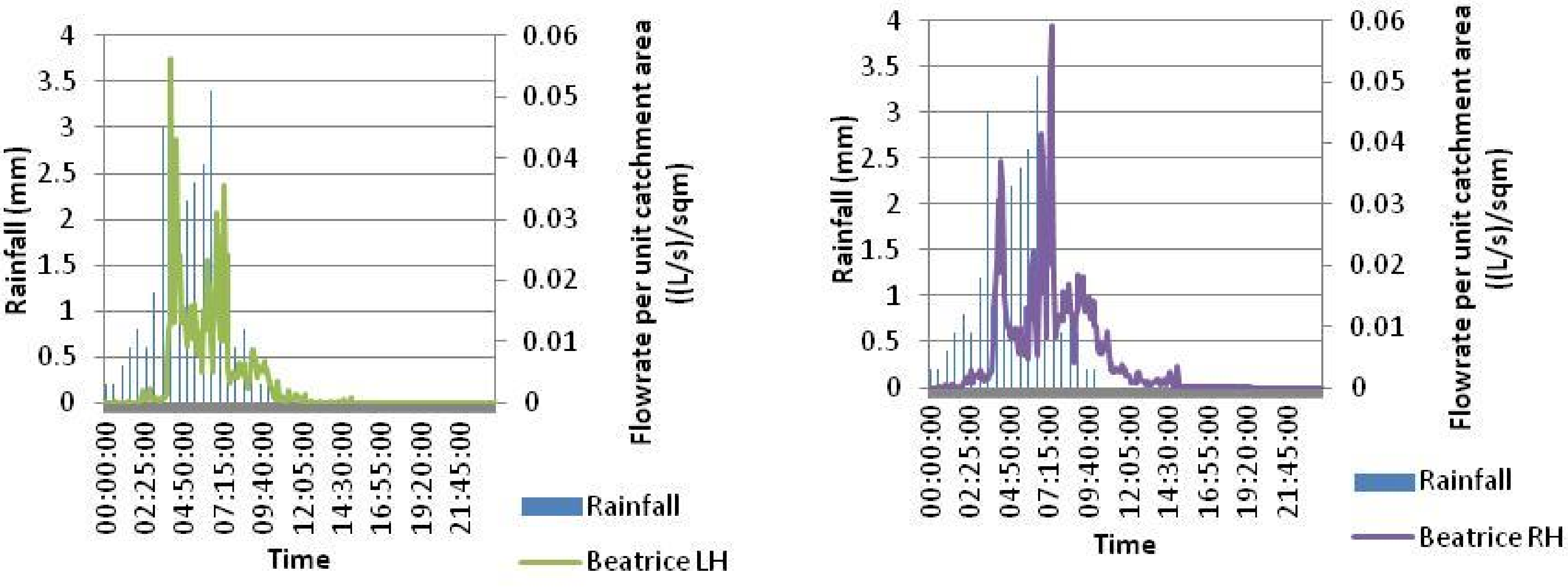
Figure 43 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline Estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial attenuation and reductions in the peak flows from the green roofs compared to the control roofs (Table 4.i). Maximum peak flow reduction recorded was 97%. Peak flows were also delayed (Table 4.ii), the longest delay being 5 hours. Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 4. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 26.4 mm rain event on the 9th November 2016 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	88%	97%	80%
Beatrice RH	88%	97%	80%

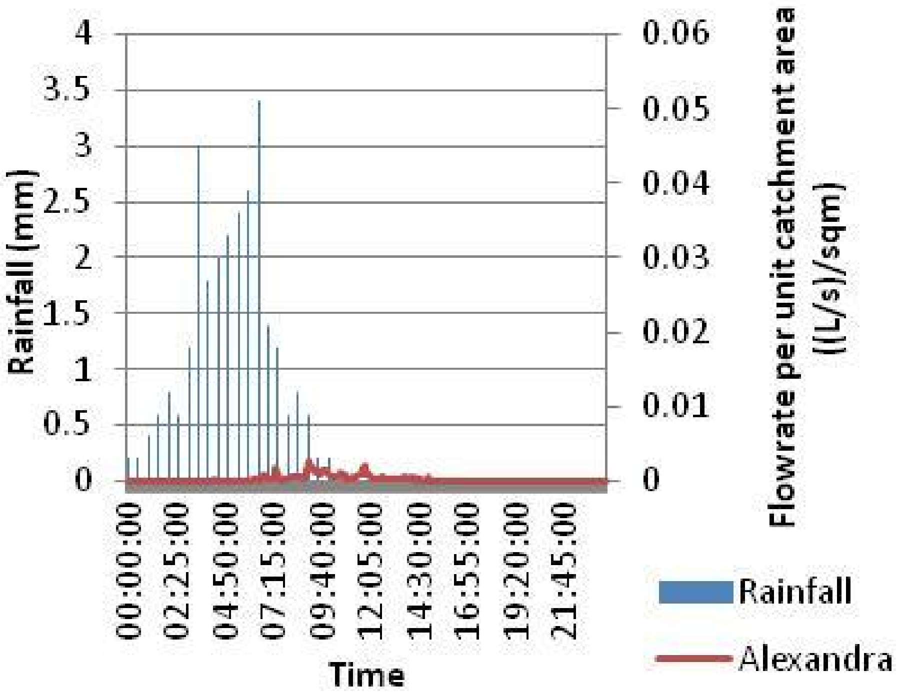
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	05:00:00	05:00:00	05:00:00
Beatrice RH	01:40:00	01:40:00	01:40:00



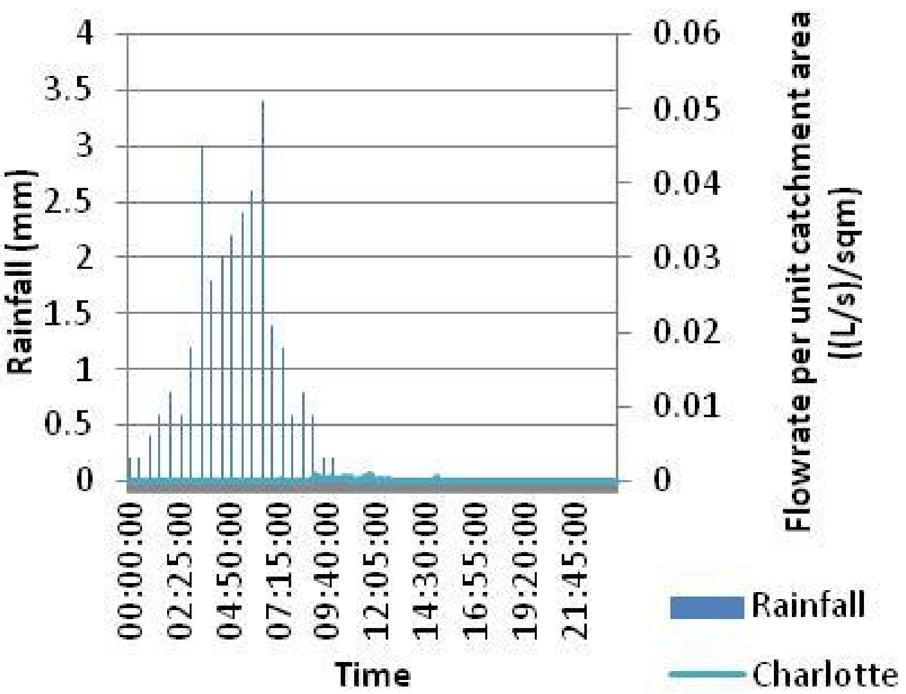
i)

ii)

Figure 43. (see below)

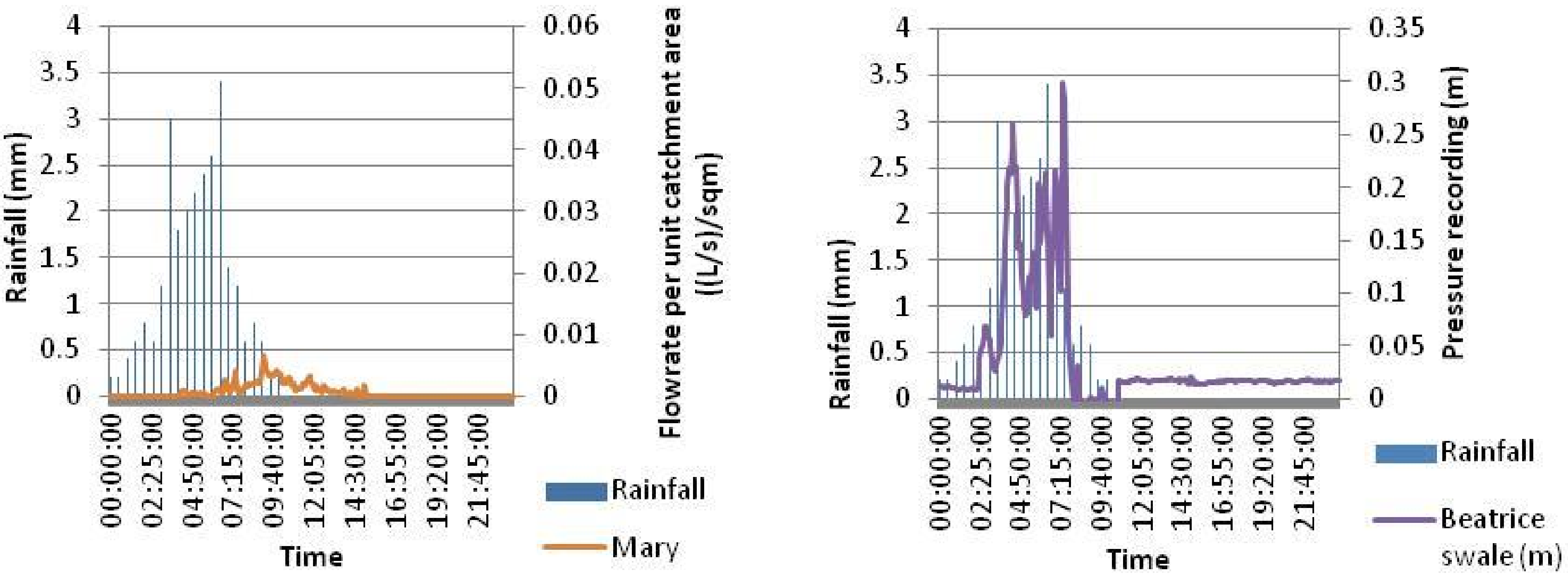


iii)



iv)

Figure 43. (see below)



v) vi)

Figure 43. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 9th November 2016. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pramshed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 43.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period of time following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

Winter event 2 - 20th November 2016

Figure 44 shows the prevailing weather patterns preceding the rain event on the 20th November 2016.

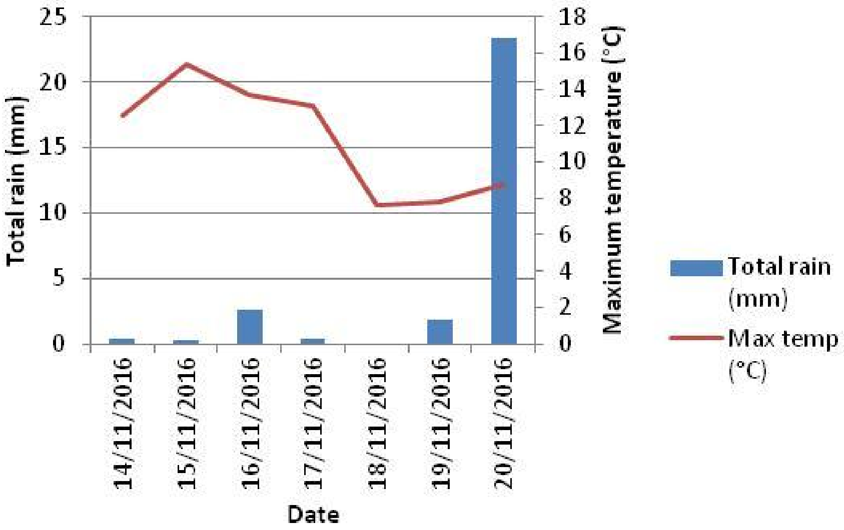


Figure 44. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 23.4 mm on 20th November 2016.

Table 5 contains the attenuation performance of the pramshed roofs during the rain event on the 20th November 2016.

Table 5. Pramshed green roof water attenuation performance during a rain event on the 20th November 2016. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	23.4	22	484	67
Charlotte	23.4	32	748.8	50
Mary	23.4	33.25	778.1	76
Average				**64.3**

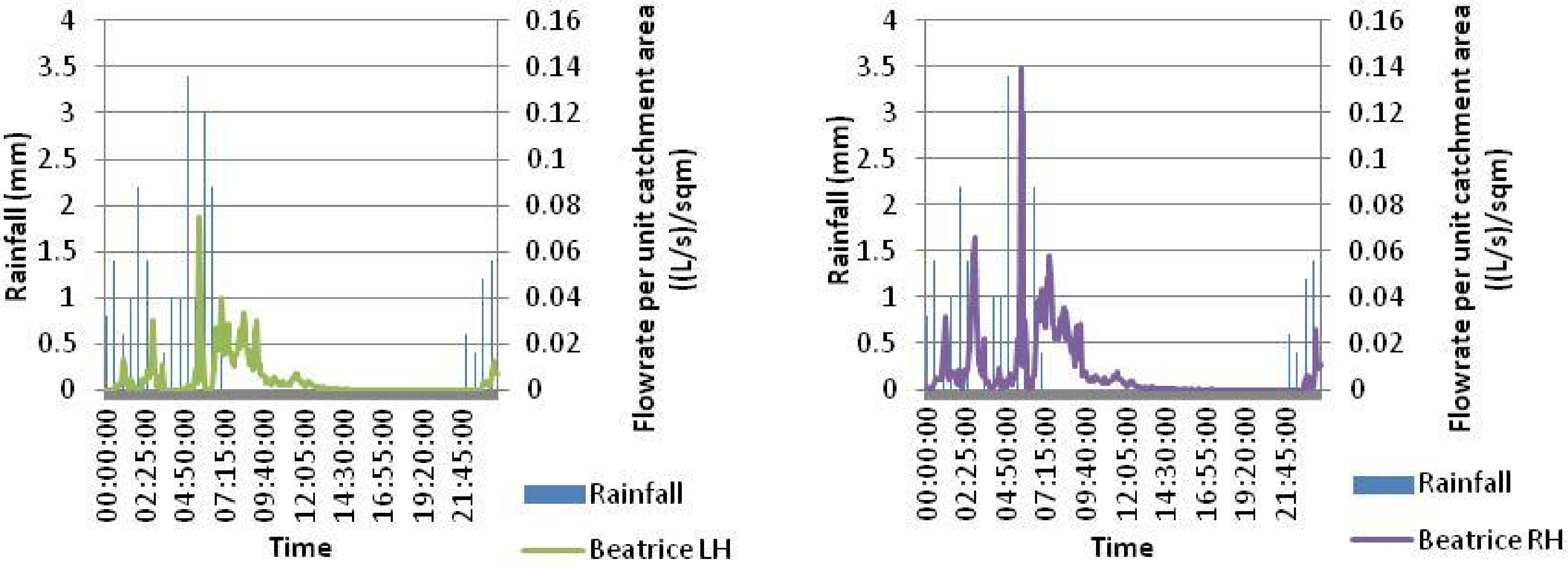
Figure 45 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline Estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial attenuation and reductions in the peak flows from the green roofs compared to the control roofs (Table 6.i). Maximum peak flow reduction recorded was 51%. Negative reductions were recorded for Charlotte and Alexandra, but these were delayed substantially compared to the control roofs and may have been the consequence of small blockages in the v-notches. All peak flows from the green roofs were delayed by 2 hours and 40 minutes (Table 6.ii). Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 6. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 23.4 mm rain event on the 20th November 2016 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	-7.69%	-50.54%	25.38%
Beatrice RH	30.00%	2.15%	51.50%

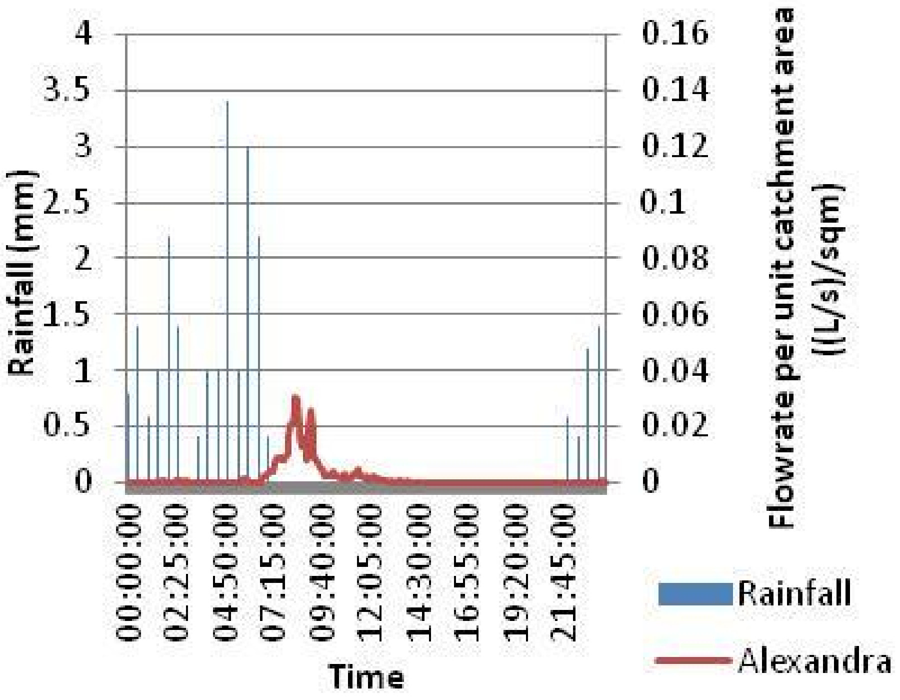
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	02:40:00	02:40:00	02:40:00
Beatrice RH	02:40:00	02:40:00	02:40:00

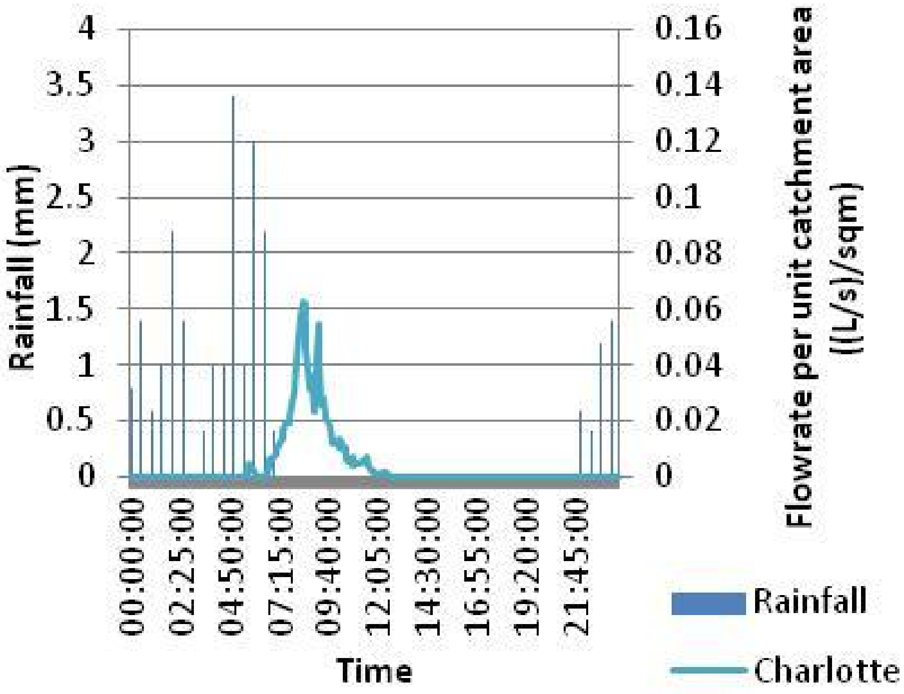


i)

ii)

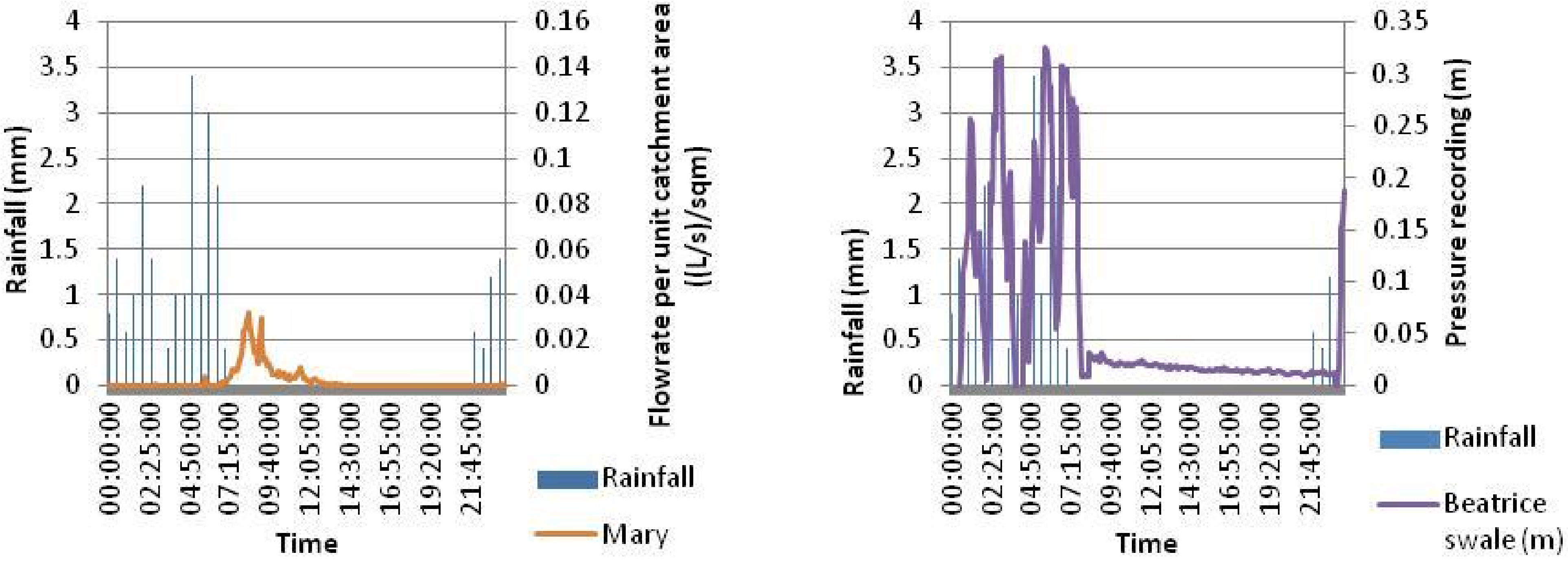
Figure 45. (see below)





iii) **iv)**

Figure 45. (see below)



v) vi)

Figure 45. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 20th November 2016. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 45.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

Winter event 3 - 12th January 2017

Figure 46 shows the prevailing weather patterns preceding the rain event on the 12th January 2017.

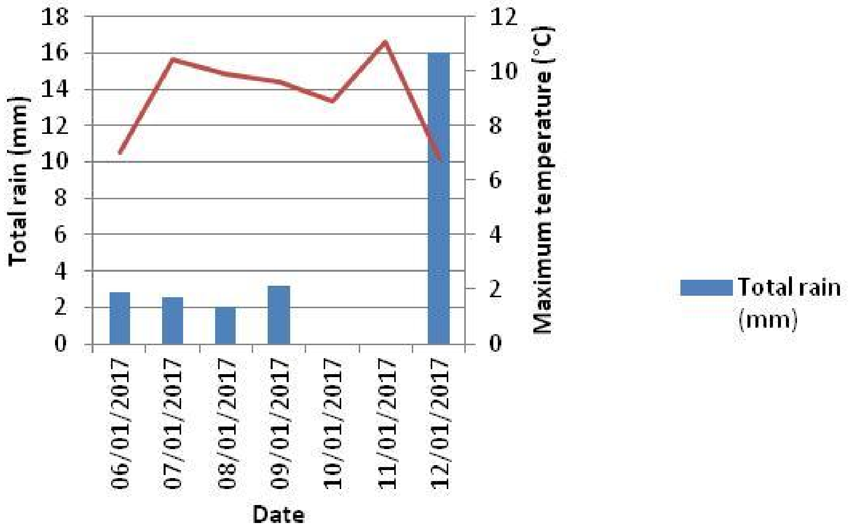


Figure 46. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 16 mm on 12th January 2017.

Table 7 contains the attenuation performance of the pramshed roofs during the rain event on the 12th January 2017.

Table 7. Pramshed green roof water attenuation performance during a rain event on the 12th January 2017. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	16	22	352	89
Charlotte	16	32	512	91
Mary	16	33.5	532	93
Average				**91**

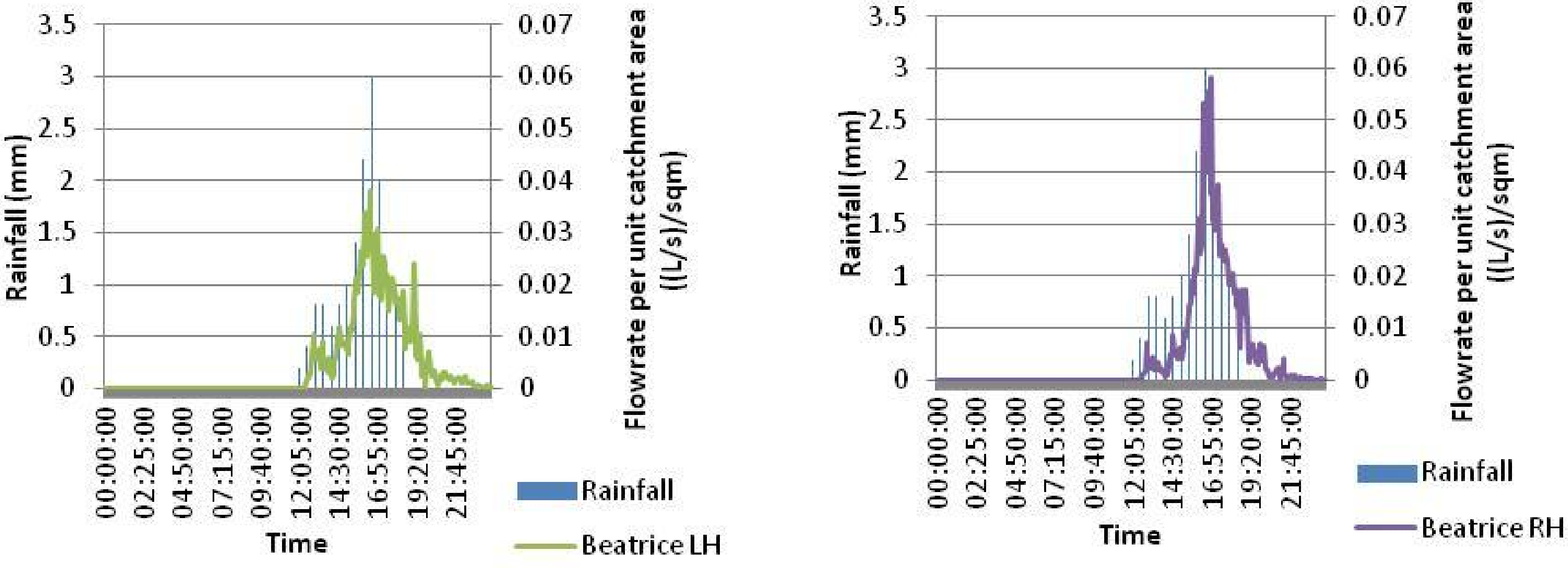
Figure 47 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline Estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial attenuation and reductions in the peak flows from the green roofs compared to the control roofs (Table 8.i). Maximum peak flow reduction recorded was 86%. In general peak flows were delayed (Table 8.ii), with the maximum delay being 40 minutes. Two of the peak flows were not delayed and were in fact earlier than the peak flow from Beatrice RH (Table 8.ii). However, both of these peak flows were substantially reduced compared to the Beatrice RH peak flow (Table 8. i) Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 8. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 16 mm rain event on the 12th January 2017 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	71.21%	66.67%	78.79%
Beatrice RH	81.00%	78.00%	86.00%

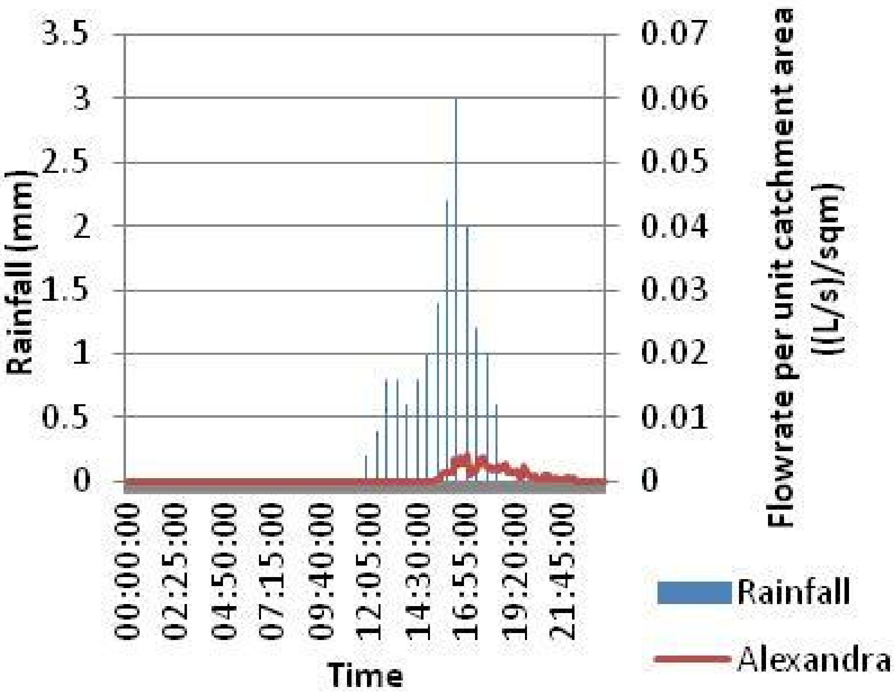
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	00:40:00	00:10:00	00:15:00
Beatrice RH	00:10:00	-00:20:00	-00:05:00



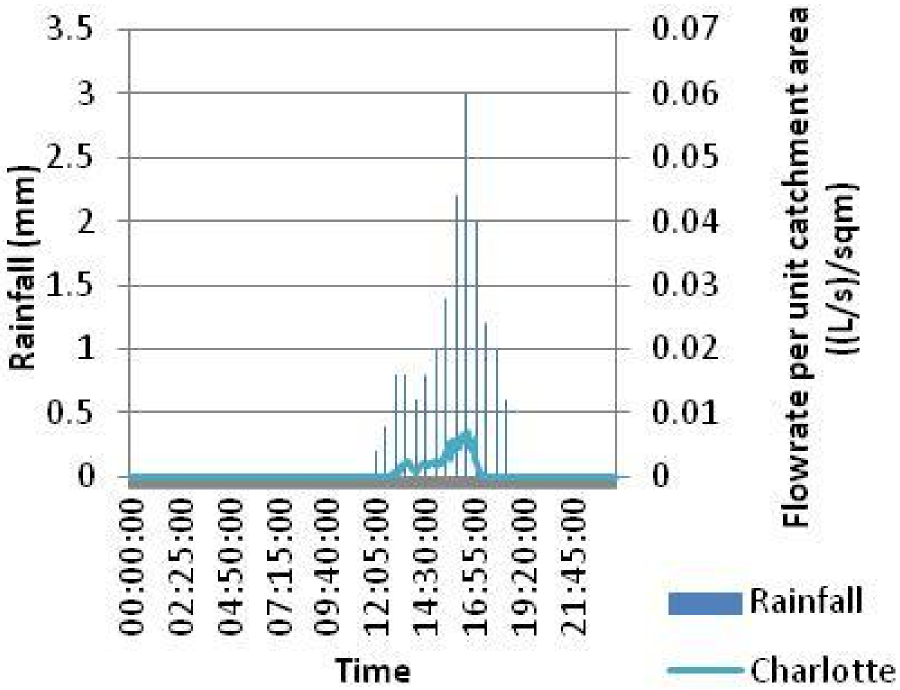
i)

ii)

Figure 47. (see below)

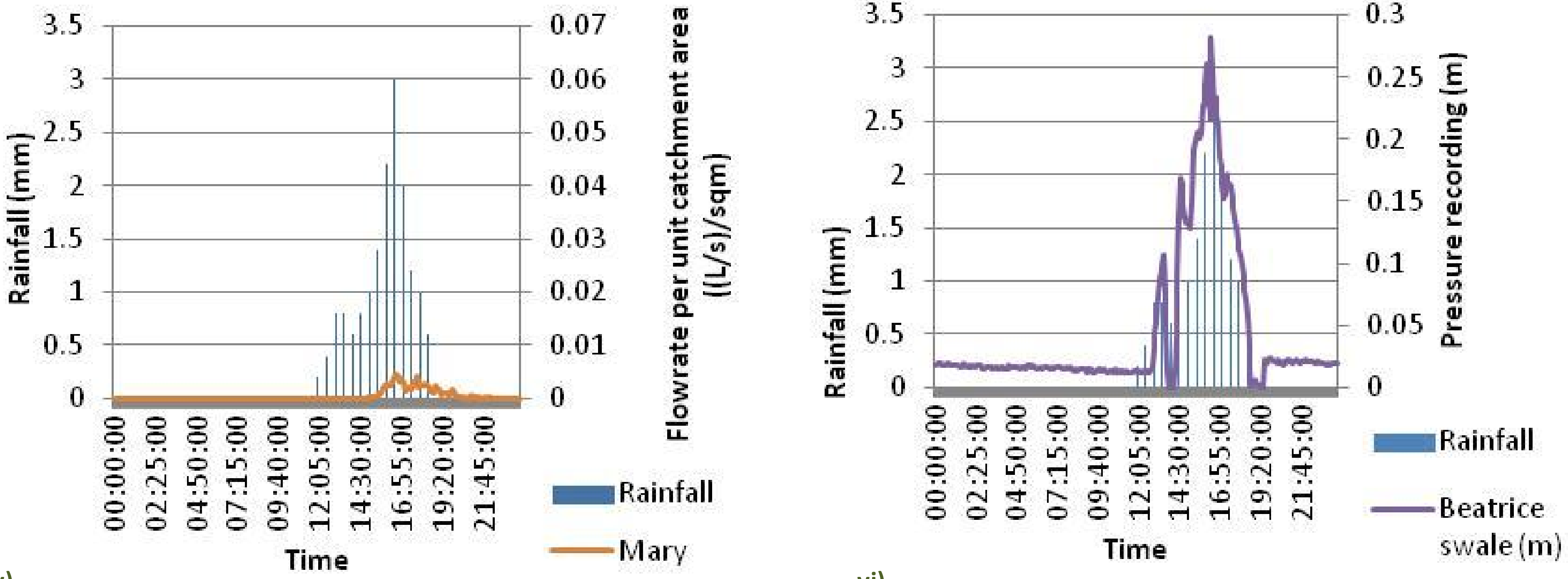


iii)



iv)

Figure 47. (see below)



v) vi)

Figure 47. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 12th January 2017. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 47.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

Winter event 4 - 21st November 2016

Figure 48 shows the prevailing weather patterns preceding the rain event on the 21st November 2016.

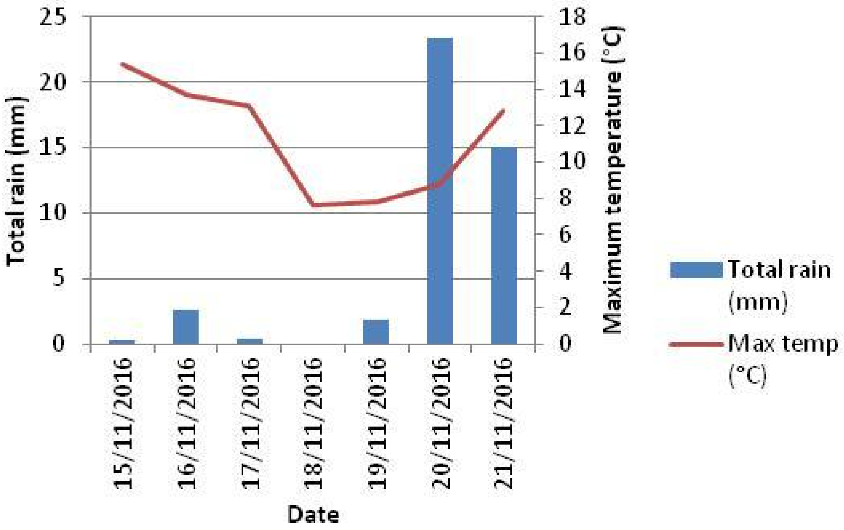


Figure 48. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 15 mm on 21st November 2016.

Table 9 contains the attenuation performance of the pramshed roofs during the rain event on the 21st November 2016.

Table 9. Pramshed green roof water attenuation performance during a rain event on the 21st November 2016. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	15	22	321.2	63
Charlotte	15	32	80	84
Mary	15	33.5	498.8	92
Average				**80**

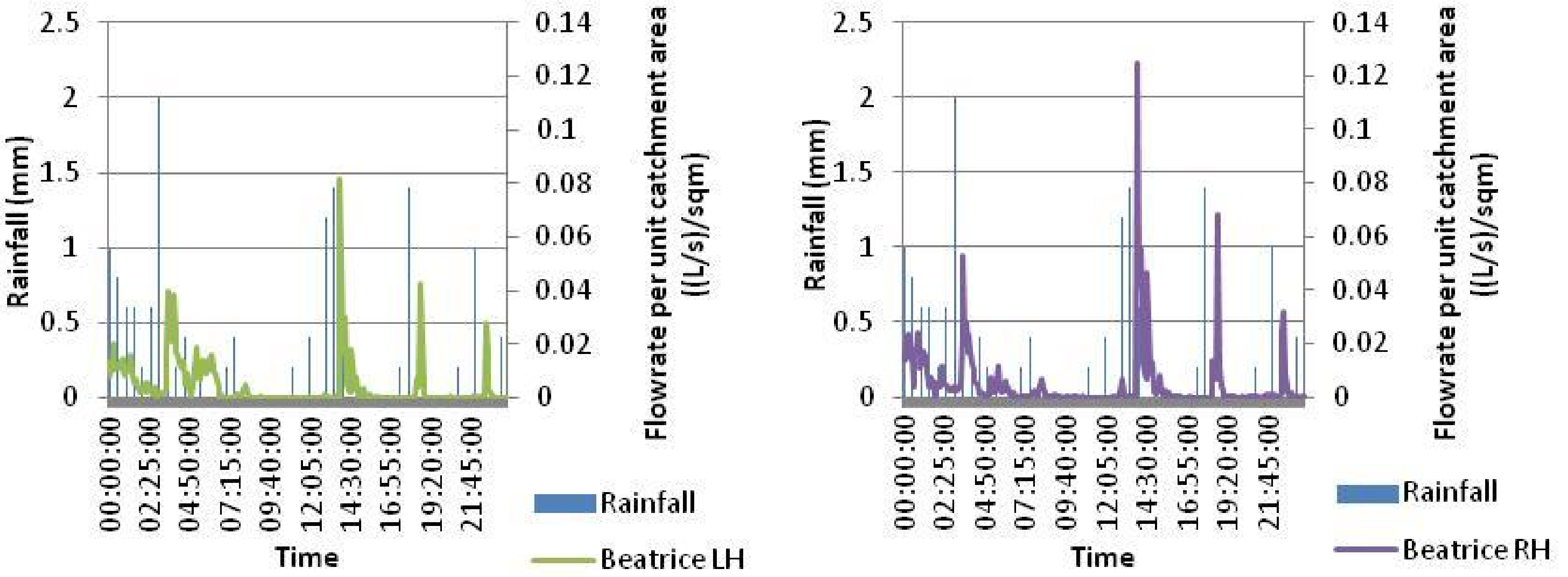
Figure 49 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline Estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial attenuation and reductions in the peak flows from the green roofs compared to the control roofs (Table 10.i). Maximum peak flow reduction recorded was 91%. Peak flows were delayed (Table 10.ii), with the maximum delay being 4 hours and 55 minutes. Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 10. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 15 mm rain event on the 21st November 2016 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	64.86%	52.68%	86.62%
Beatrice RH	77.11%	69.17%	91.28%

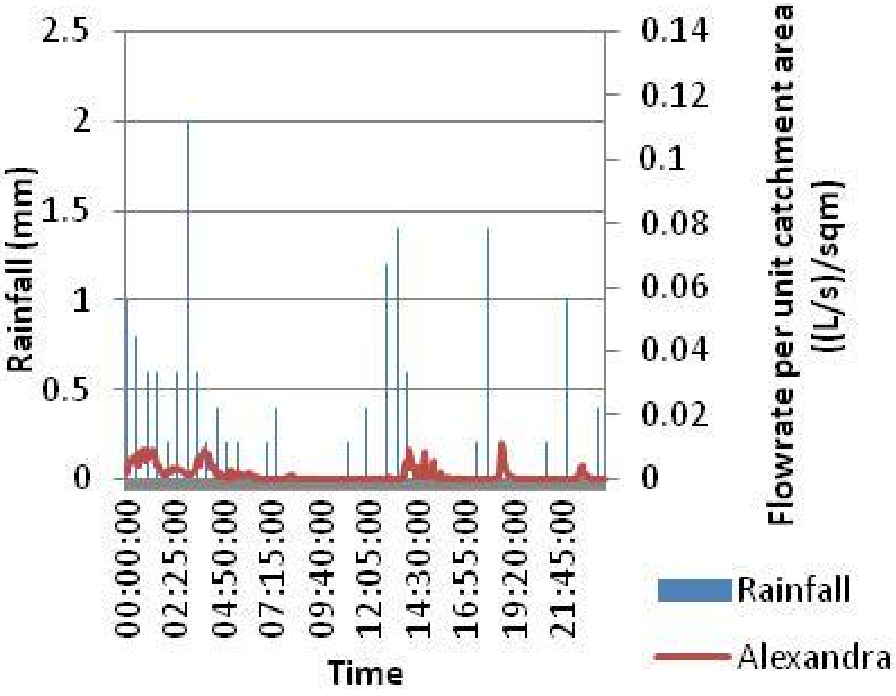
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	04:50:00	01:00:00	04:55:00
Beatrice RH	04:45:00	00:55:00	04:50:00



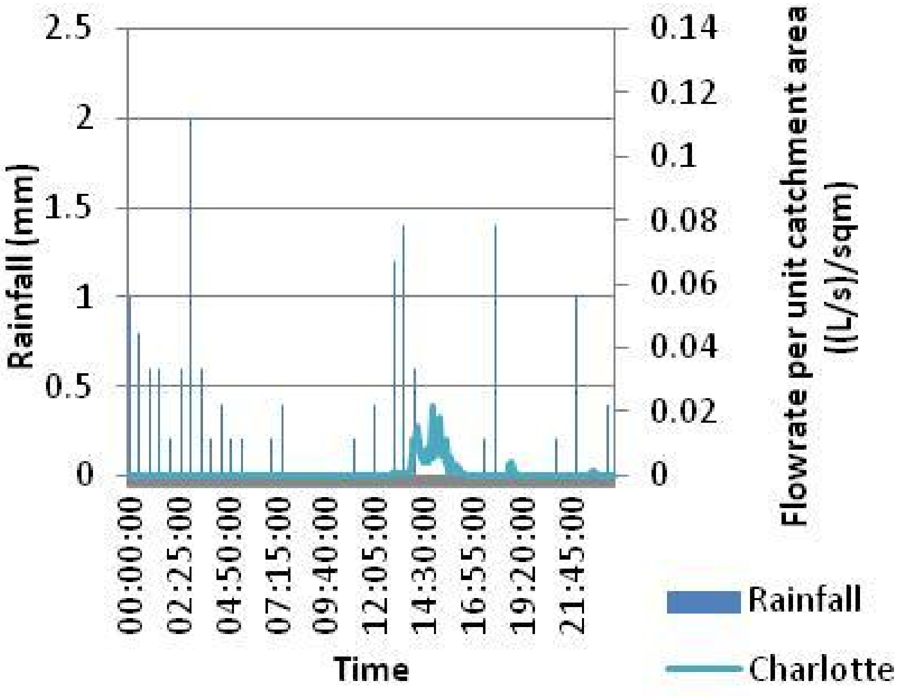
i)

ii)

Figure 49. (see below)

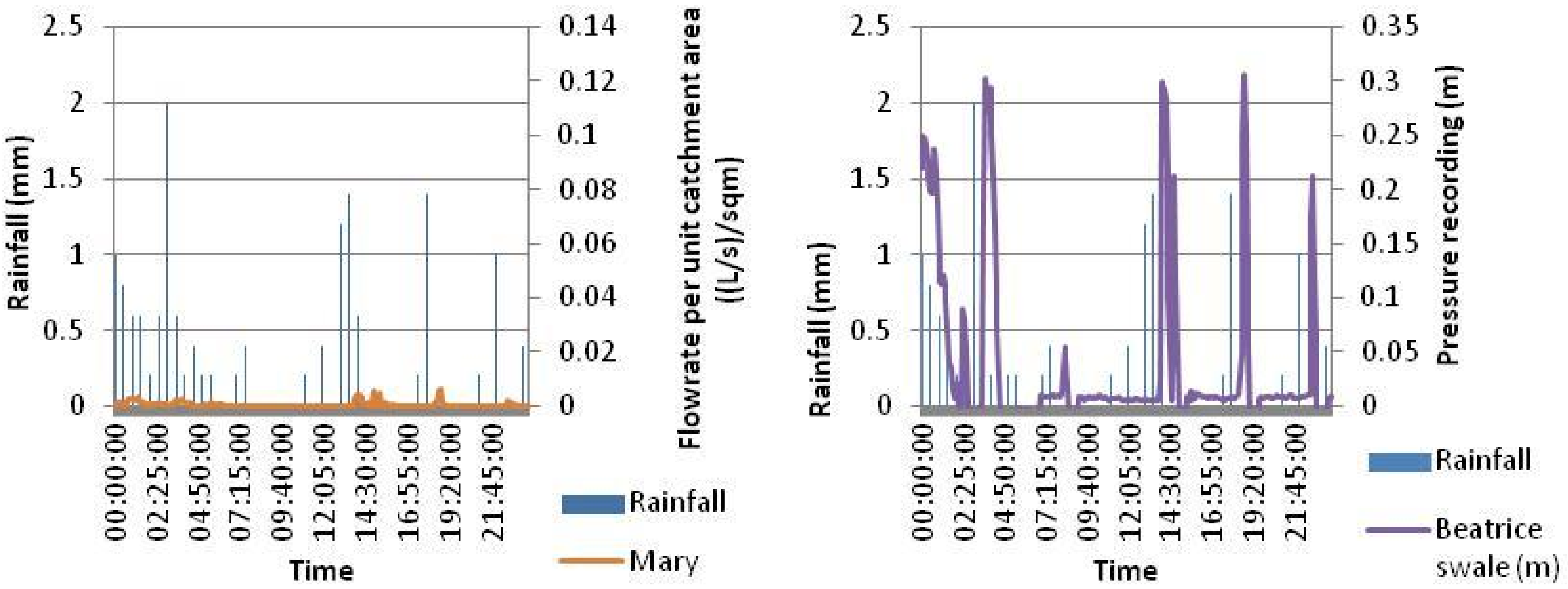


iii)



iv)

Figure 49. (see below)



v)

vi)

Figure 49. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 21st November 2016. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 49.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

Winter event 5 - 27th February 2017

Figure 50 shows the prevailing weather patterns preceding the rain event on the 27th February 2017.

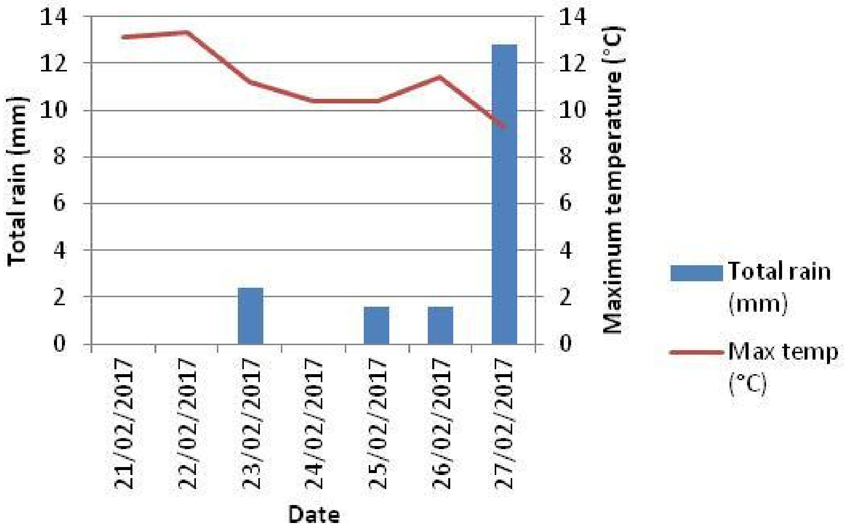


Figure 50. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 12.8 mm on 27th February 2017.

Table 11 contains the attenuation performance of the pramshed roofs during the rain event on the 27th February 2017.

Table 11. Pramshed green roof water attenuation performance during a rain event on the 27th February 2017. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	**Total rain (mm)**	**Catchment area (m)**	**Volume of rainfall in catchment area (L)**	**Attenuation (%)**
Alexandra	12.8	22	281.6	91
Charlotte	12.8	32	409.6	71
Mary	12.8	33.5	425.6	86
Average				**83**

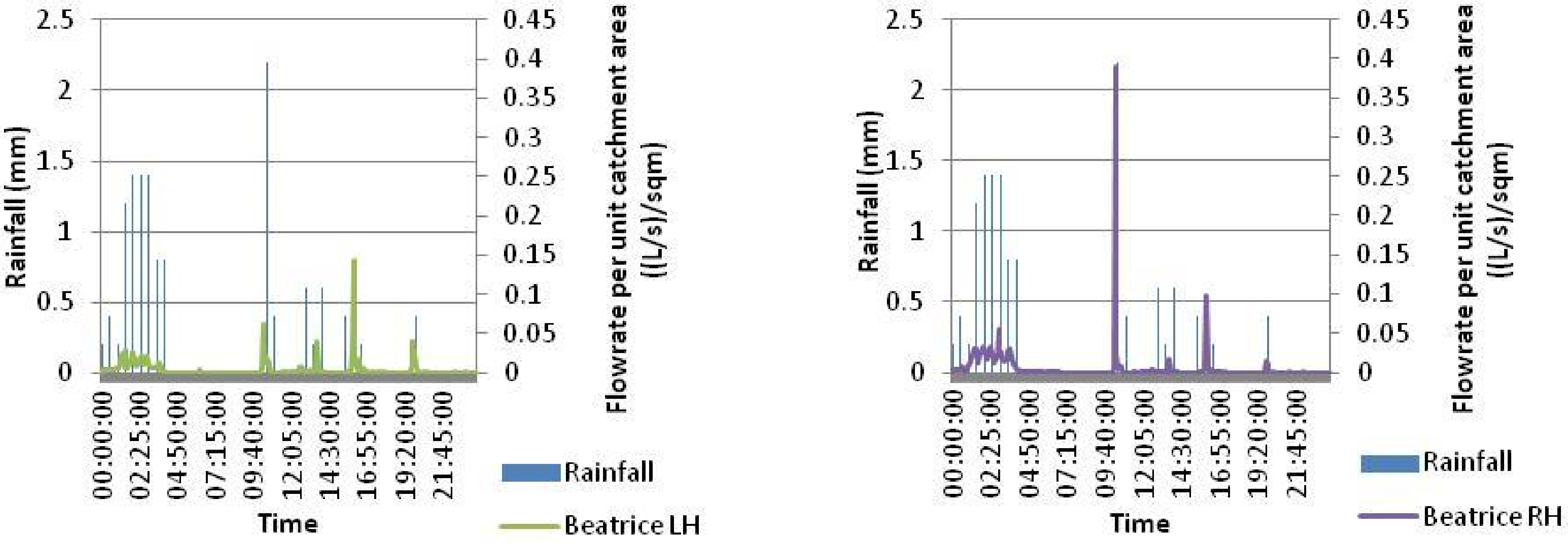
Figure 51 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline Estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial attenuation and reductions in the peak flows from the green roofs compared to the control roofs (Table 12.i). Maximum peak flow reduction recorded was 92%. Peak flows were delayed (Table 12.ii), with the maximum delay being 5 hours and 50 minutes. Peak flow from Charlotte was recorded as being 4 hours and 10 minutes before the peak flow from Beatrice LH. This was an anomaly created by the peak flow from Charlotte being during an early period of rain during the rain event and the peak flow from Beatrice LH being during a later period of rain during the same event. Nevertheless, peak flow was reduced by 77% for the Charlotte run off compared to the maximum from the control roof. Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 12. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 12.8 mm rain event on the 27th February 2017 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	74.54%	77.17%	63.35%
Beatrice RH	90.62%	91.59%	86.49%

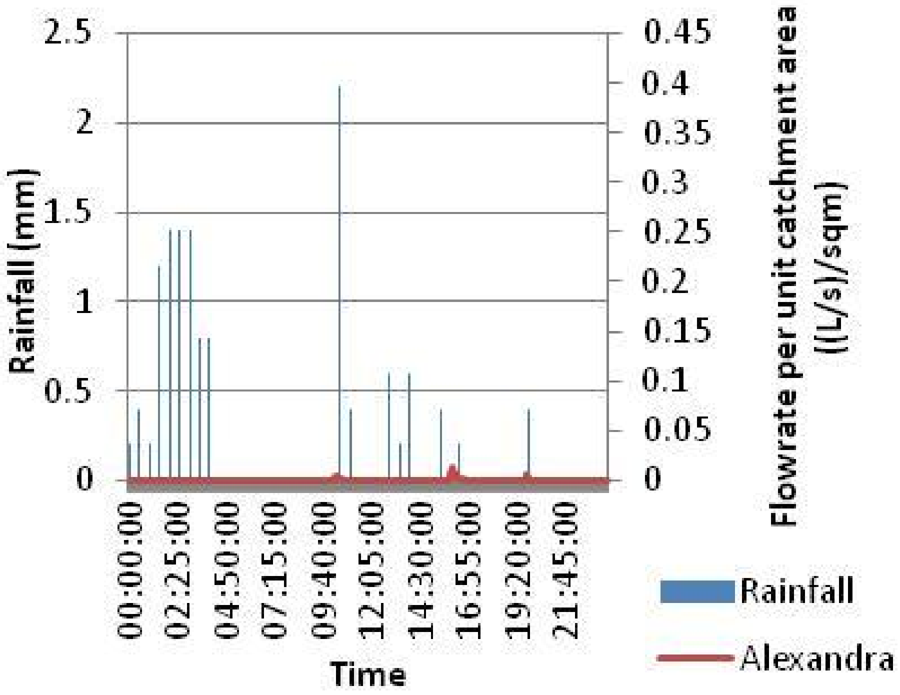
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	00:05:00	-00:04:10	00:05:00
Beatrice RH	05:50:00	01:35:00	05:05:00



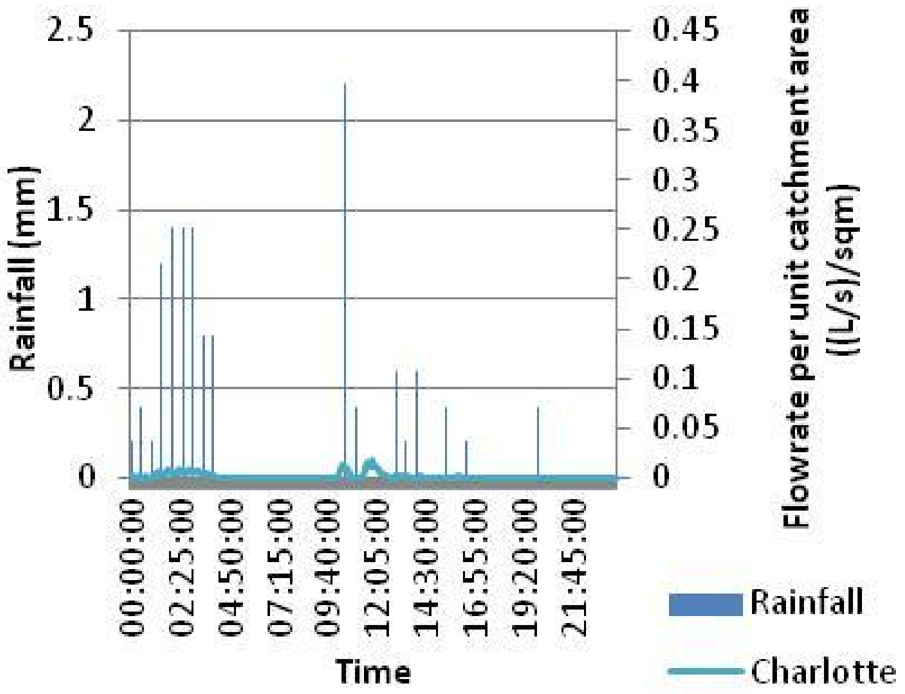
i)

ii)

Figure 51. (see below)

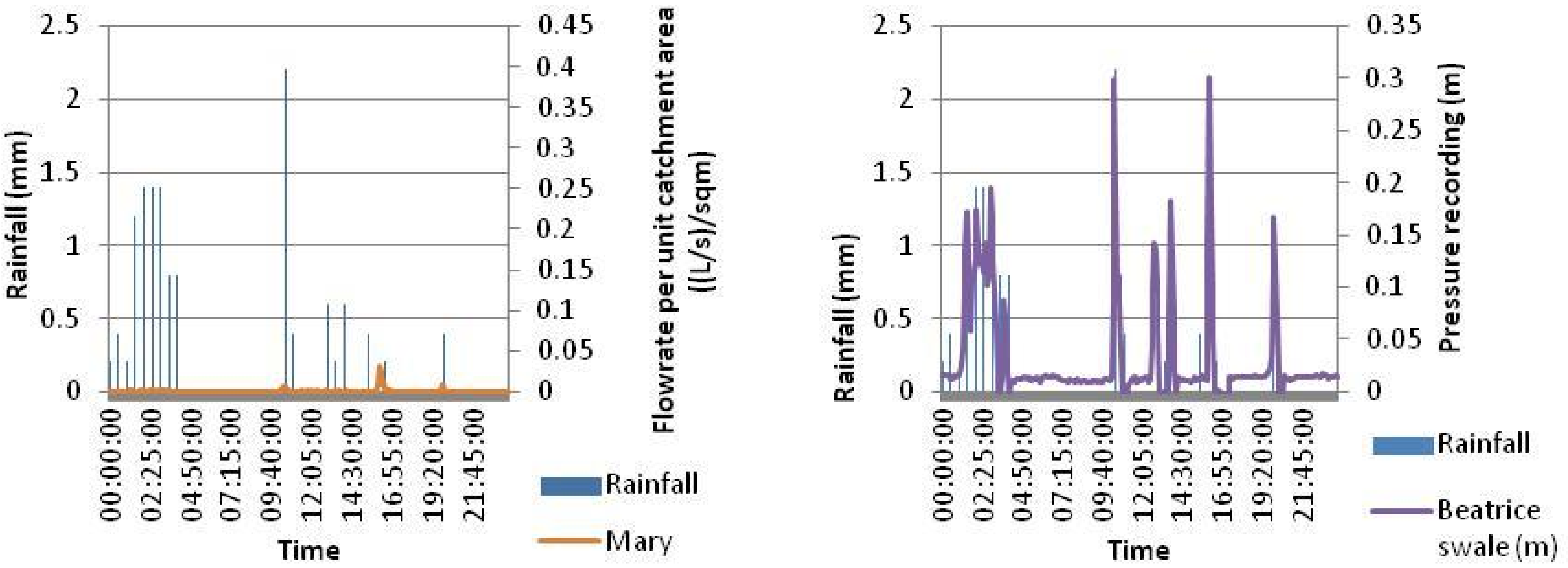


iii)



iv)

Figure 51. (see below)



v)

vi)

Figure 51. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 27th February 2017. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 51.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

Winter events summary

Data from the five largest winter events indicated that the SuDS systems being monitored were continuing to perform as designed. Beatrice swale received substantial volumes of rainfall during these events and, despite the underlying substrate being more saturated than it would be in the summer, the rainfall entering the swale appeared to infiltrate rapidly following the cessation of the each period of rainfall. This occurred for all magnitudes and intensities of natural rain events monitored.

The pramshed roofs continued to absorb the majority of the rain that fell onto them. This was quantified in terms of substantial reductions in overall run off and peak flow, and delays in peak flow. In terms of overall reduction in stormwater runoff (compared to the total rainfall on the roof areas), attenuation ranged from a maximum of 99% to a minimum of 50%. Reduction in peak flow ranged from a maximum of 97% to a minimum of -50% (although this may have been an anomalous result due to a blockage in the v-notch). Peak flow rates were delayed by as much as 5 hours and 50 minutes. Under the rare occurrence that peak flow occurred earlier from the green roofs than the control roof, peak flow reductions were substantial.

Summer event 1 - 9th August 2017

Figure 52 shows the prevailing weather patterns preceding the rain event on the 9th August 2017.

Table 13 contains the attenuation performance of the pramshed roofs during the rain event on the 9th August 2017.

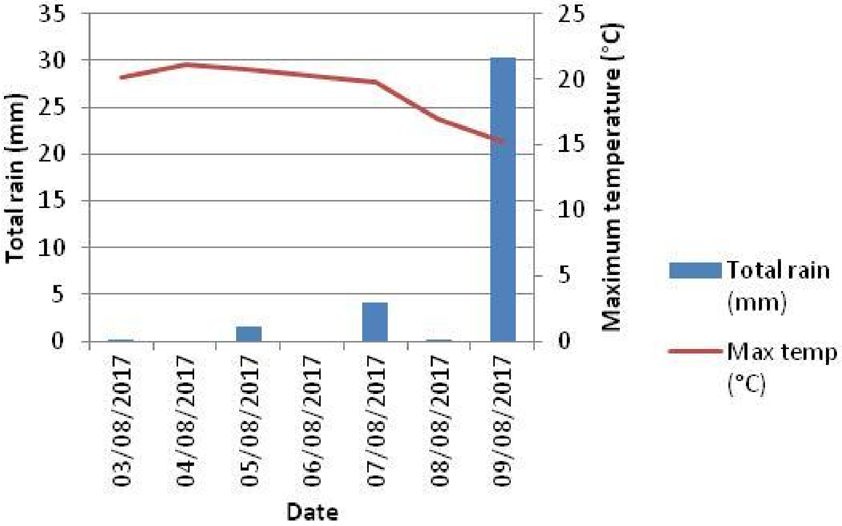


Figure 52. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 30.4 mm on 9th August 2017.

Figure 53 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline Estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Table 13. Pramshed green roof water attenuation performance during a rain event on the 9th August 2017. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

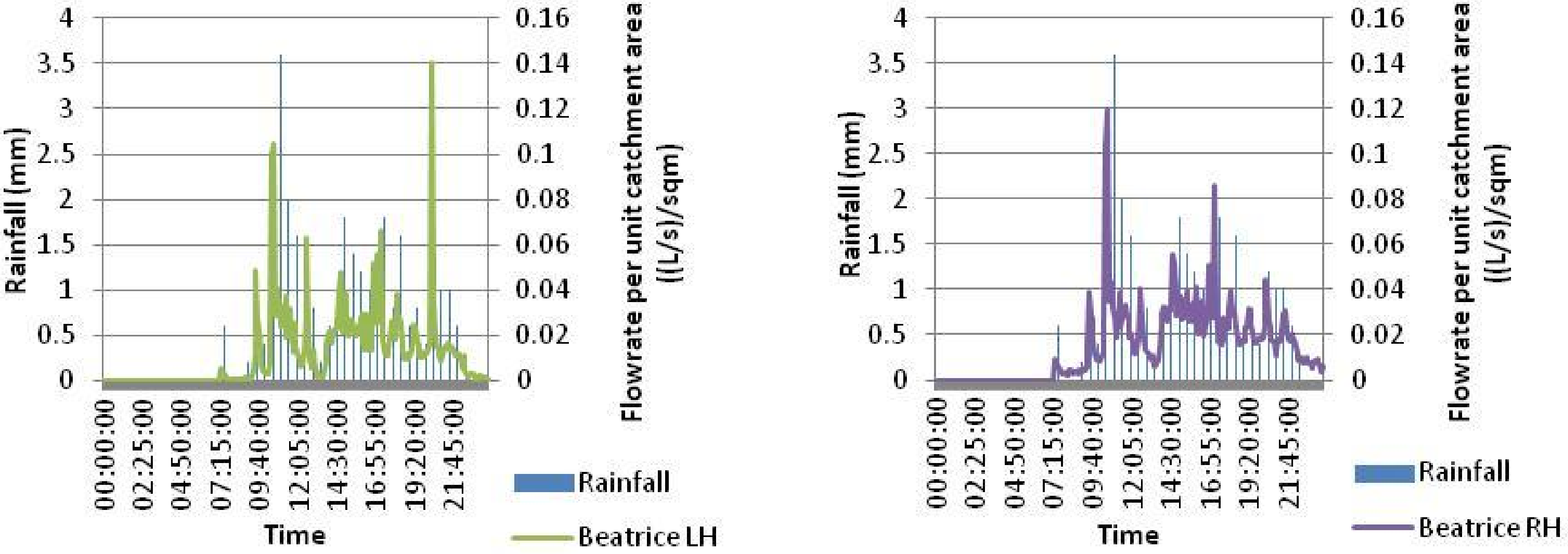
Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	30.4	22	668.8	N/A
Charlotte	30.4	32	972.8	66
Mary	30.4	33.5	1010.8	62
Average				**64**

No data was available for the Alexandra House datalogger due to a malfunction. Evidence from the roof runoff monitoring of the other green roofs was positive with substantial attenuation and reductions in the peak flows from the green roofs compared to the control roofs (Table 14.i). Maximum peak flow reduction recorded was 80%. Peak flows were delayed in relation to Beatrice RH (Table 14.ii), with the maximum delay being 4 hours and 15 minutes. The peak flow from Beatrice LH was later though meaning that peak flows from Charlotte and Mary were before the Beatrice LH peak flow. This appeared to be another anomaly created by the late peak flow from Beatrice LH in relation to the rainfall pattern. Nevertheless, peak flow was reduced by 61% and 76% respectively for the two green roofs compared to Beatrice LH. Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 14. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 30.4 mm rain event on the 9th August 2017 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	N/A	66.75%	79.88%
Beatrice RH	N/A	60.86%	76.32%

ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	N/A	-00:05:35	-07:55:00
Beatrice RH	N/A	04:15:00	00:00:00

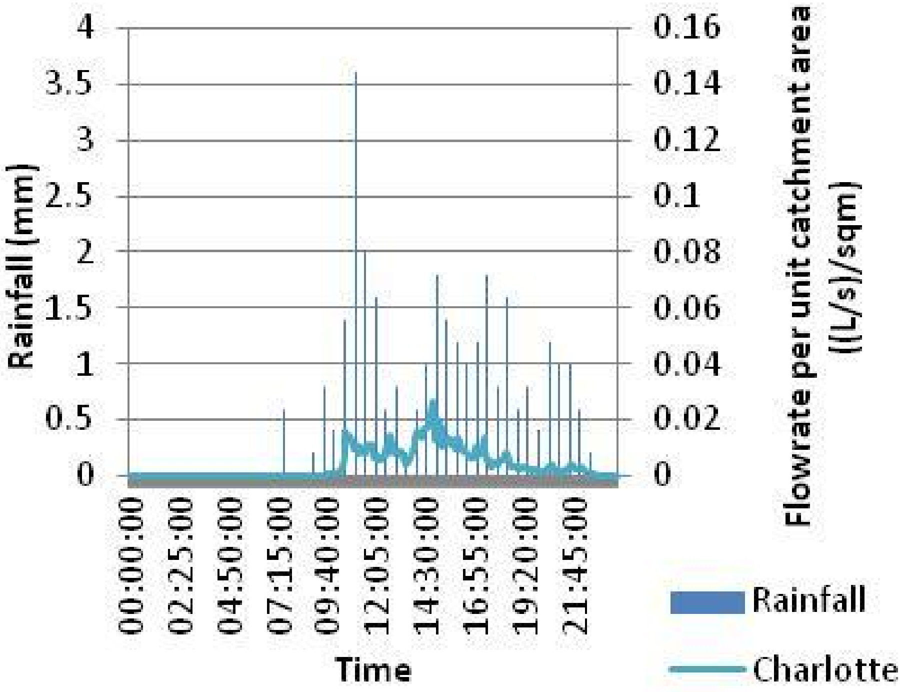


i)

ii)

Figure 53. (see below)

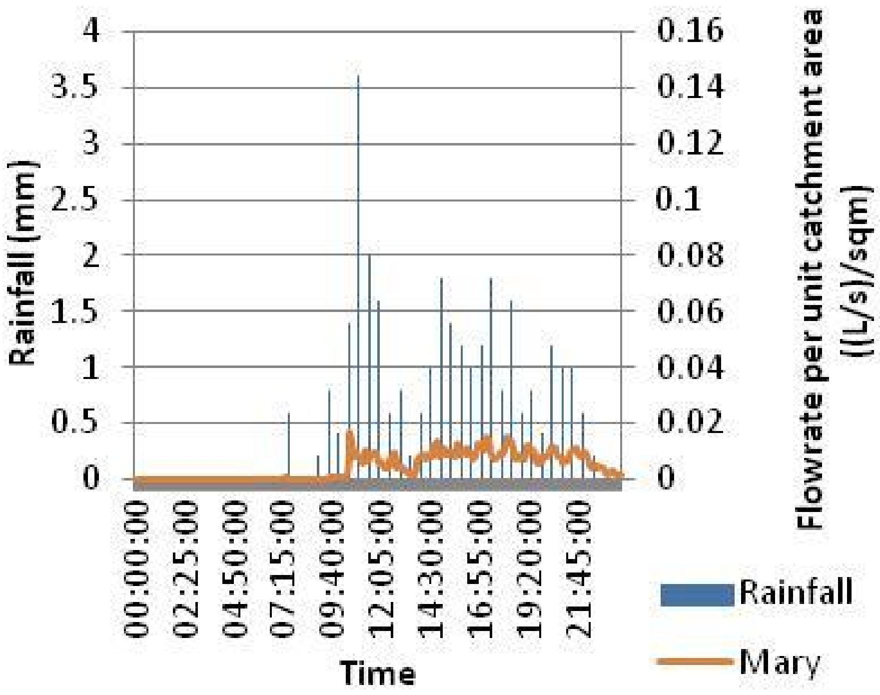
N/A



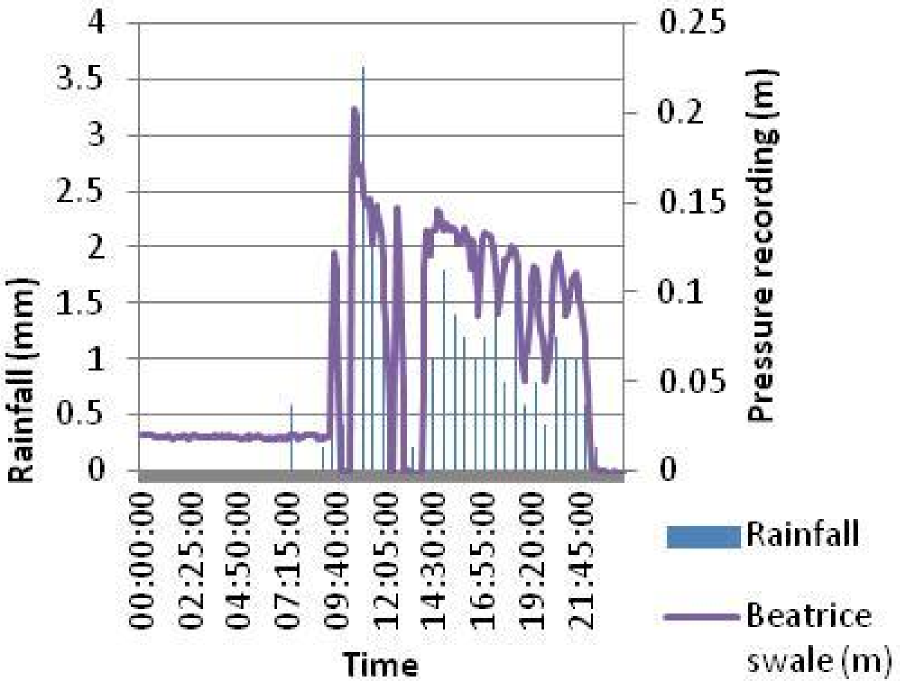
iii)

iv)

Figure 53. (see below)



v)



vi)

Figure 53. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 9th August 2017. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate (No data was available for Alexandra House (iiI) due to a datlogger malfunction), and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 53.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

Summer event 2 - 17th May 2017

Figure 54 shows the prevailing weather patterns preceding the rain event on the 17th May 2017.

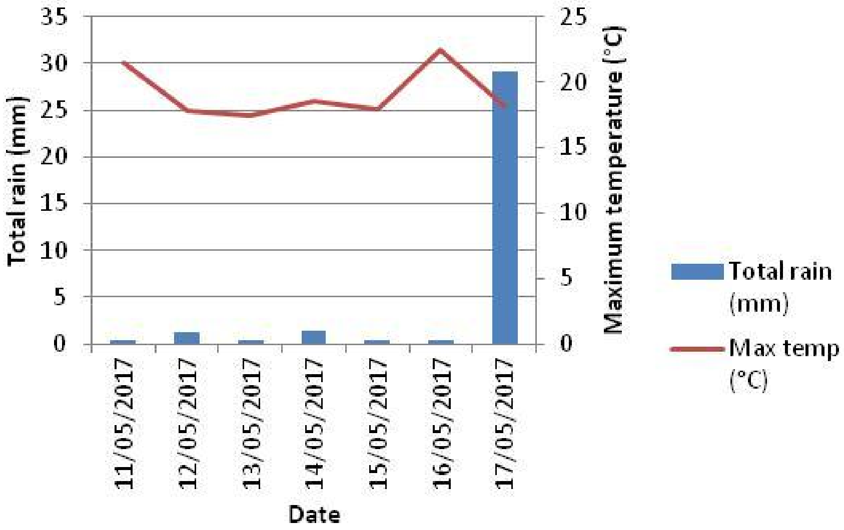


Figure 54. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 29.2 mm on 17th May 2017.

Table 15 contains the attenuation performance of the pramshed roofs during the rain event on the 17th May 2017.

Table 15. Pramshed green roof water attenuation performance during a rain event on the 17th May 2017. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	29.2	22	642.4	87
Charlotte	29.2	32	934.4	87
Mary	29.2	33.5	970.9	95
Average				**90**

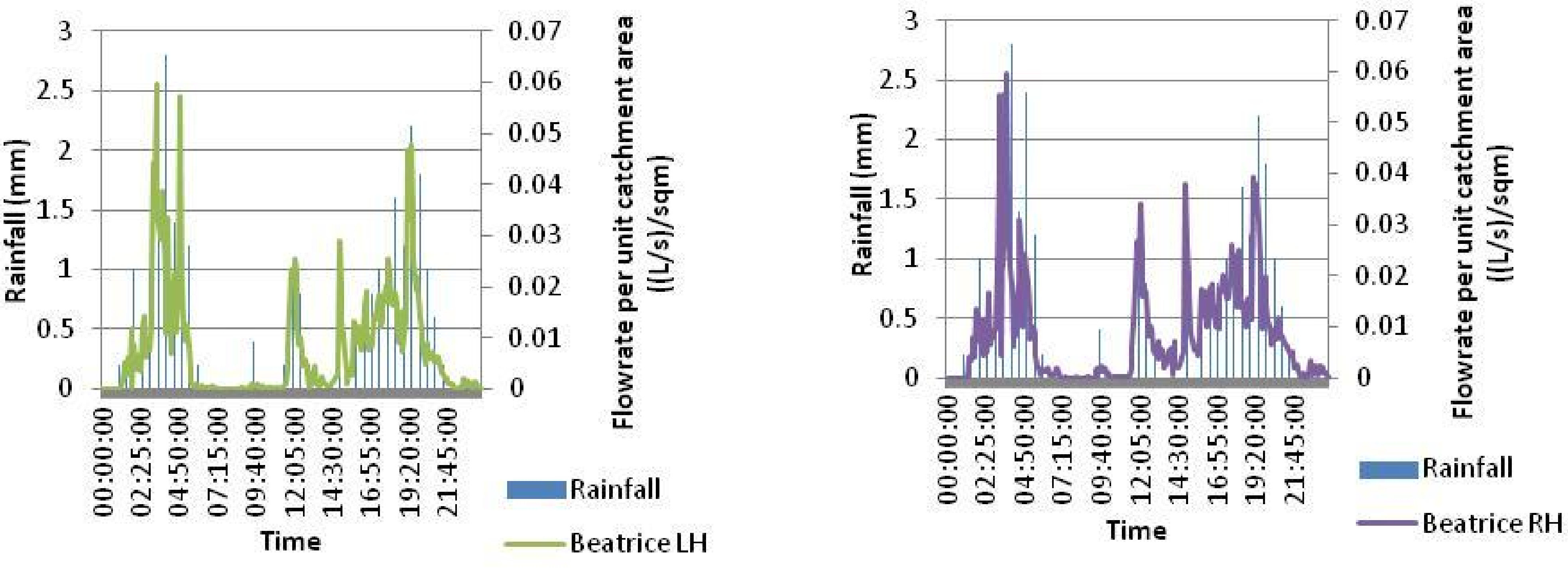
Figure 55 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline Estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial attenuation and reductions in the peak flows from the green roofs compared to the control roofs (Table 16.i). Maximum peak flow reduction recorded was 76%. Peak flows were delayed (Table 16.ii), with the maximum delay being 16 hours. Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 16. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 29.2 mm rain event on the 17th May 2017 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	62.88%	65.38%	75.87%
Beatrice RH	62.88%	65.38%	75.87%

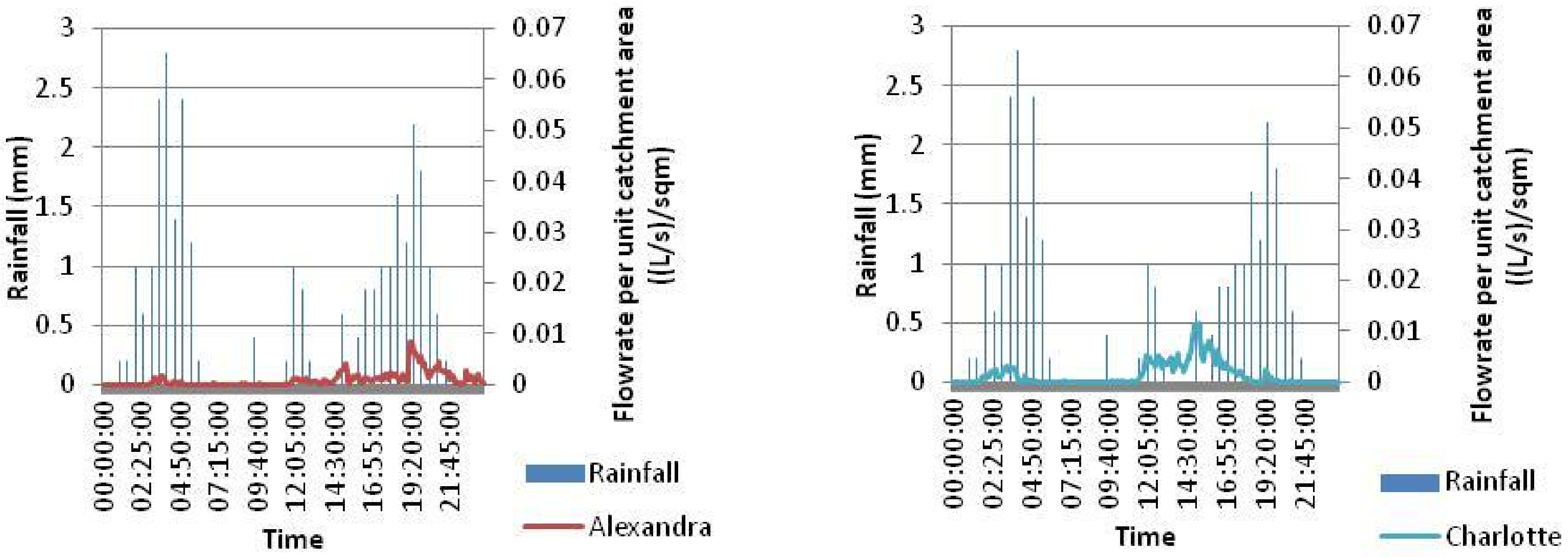
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	15:55:00	11:50:00	16:00:00
Beatrice RH	15:35:00	11:30:00	15:40:00



i)

ii)

Figure 55. (see below)



iii)

iv)

Figure 55. (see below)

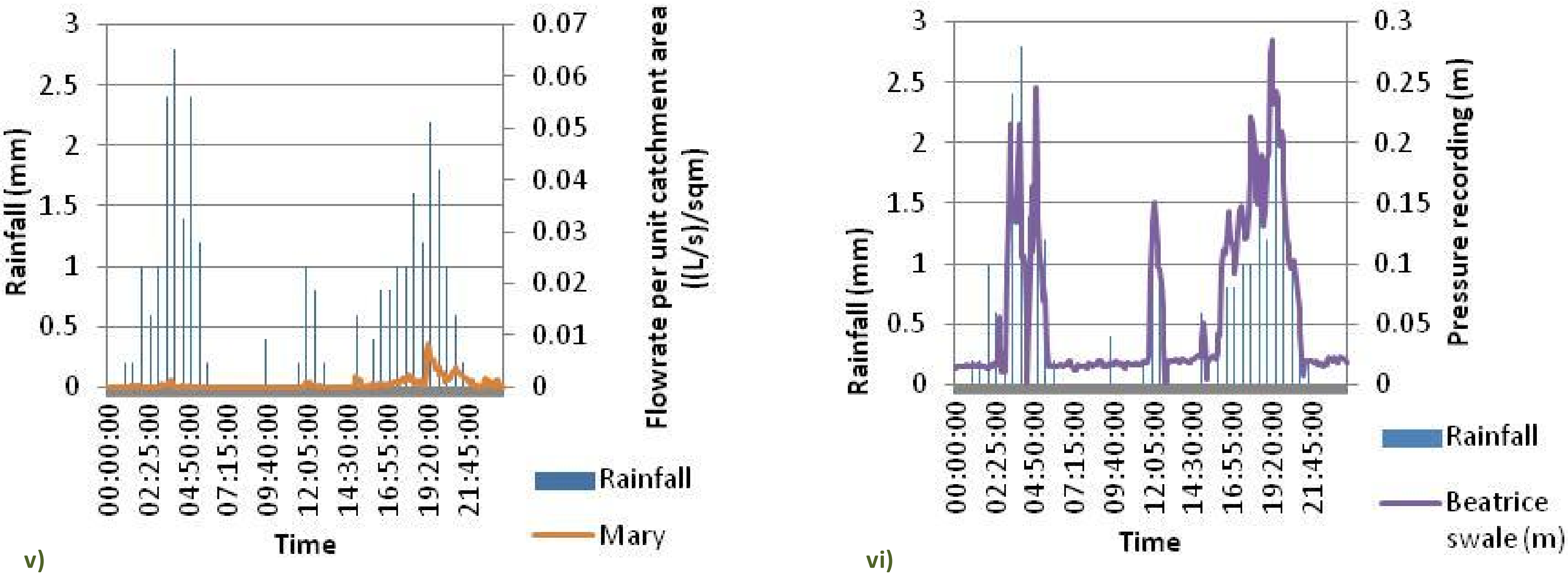


Figure 55. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 17th May 2017. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 55.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

Summer event 3 - 30th July 2017

Figure 56 shows the prevailing weather patterns preceding the rain event on the 30th July 2017.

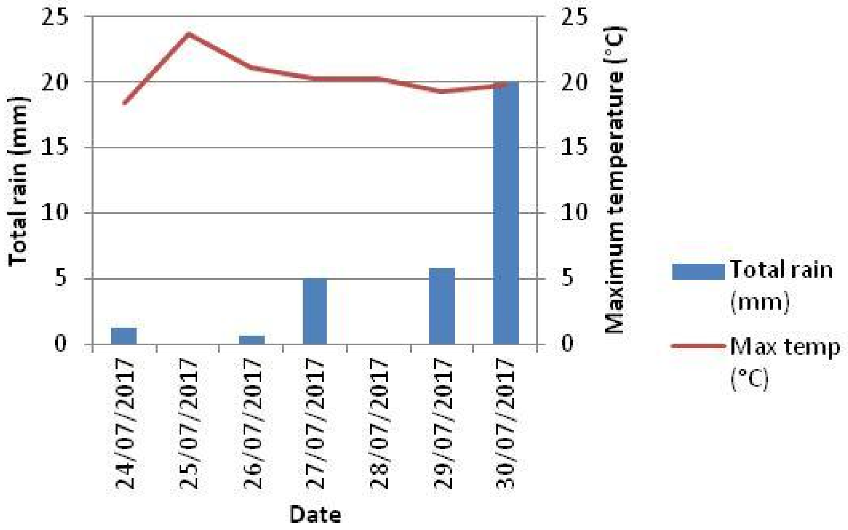


Figure 56. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 20 mm on 30th July 2017.

Table 17 contains the attenuation performance of the pramshed roofs during the rain event on the 30th July 2017.

Table 17. Pramshed green roof water attenuation performance during a rain event on the 30th July 2017. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	20	22	440	79
Charlotte	20	32	640	81
Mary	20	33.5	665	85
Average				**82**

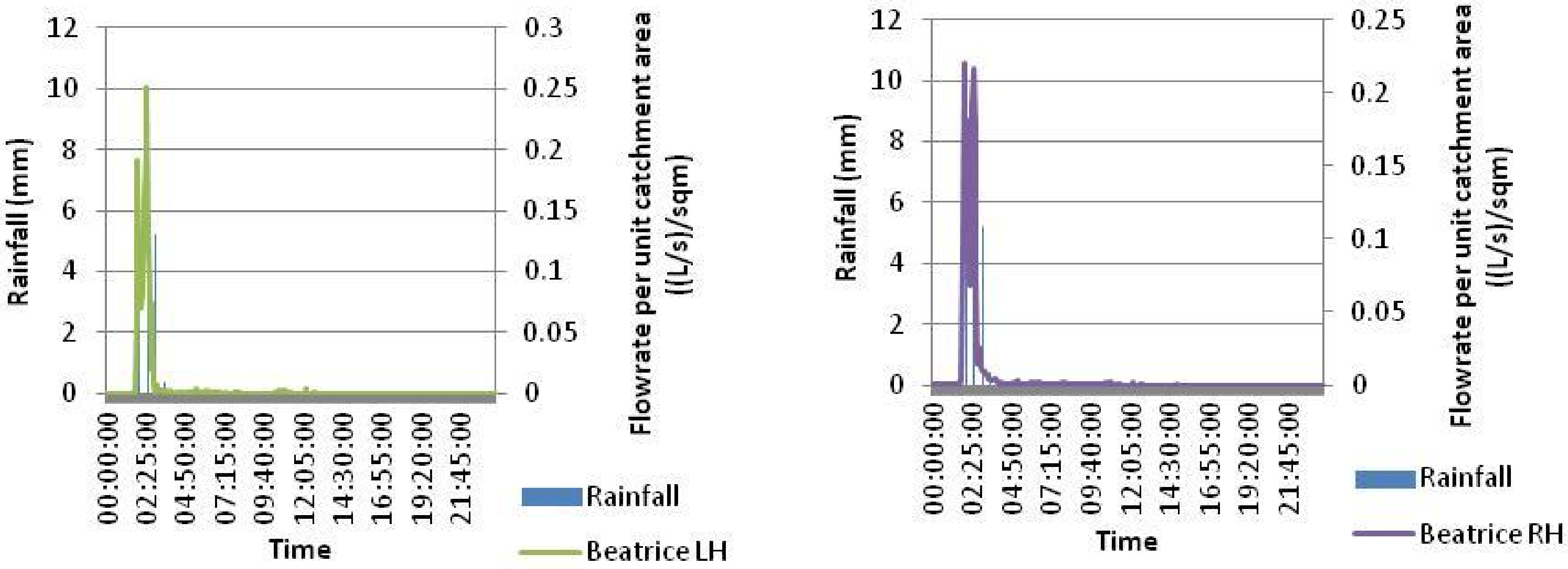
Figure 57 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline Estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial attenuation and reductions in the peak flows from the green roofs compared to the control roofs (Table 18.i). Maximum peak flow reduction recorded was 55%. Peak flows were delayed (Table 18.ii), with the maximum delay being 40 minutes. This was a short duration, high intensity rain event. As such the pram shed green roofs were less able to cope with the capacity. Nevertheless they all recorded delays and peak flow reductions and substantial attenuation compared to total rainfall (average 82%). Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 18. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 20 mm rain event on the 30th July 2017 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	40.18%	21.69%	55.25%
Beatrice RH	31.95%	10.91%	49.09%

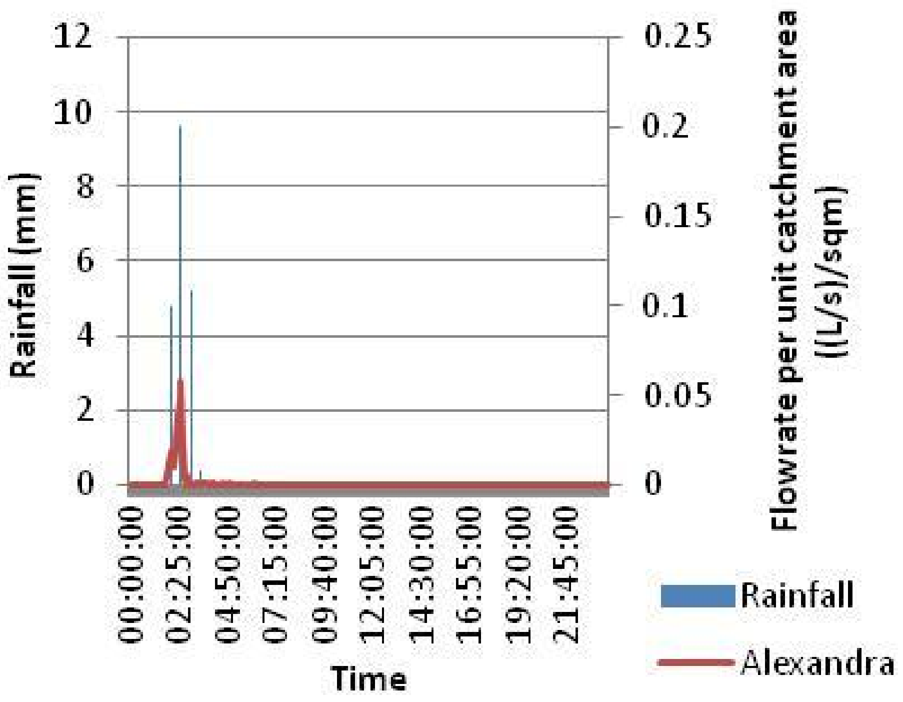
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	00:05:00	00:05:00	00:05:00
Beatrice RH	00:40:00	00:40:00	00:40:00

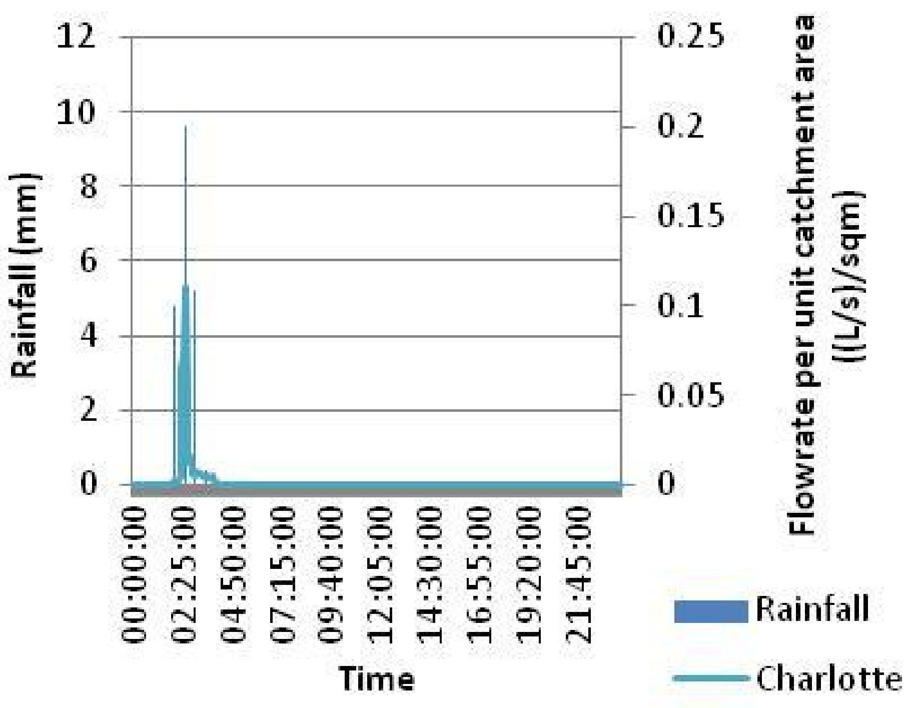


i)

ii)

Figure 57. (see below)

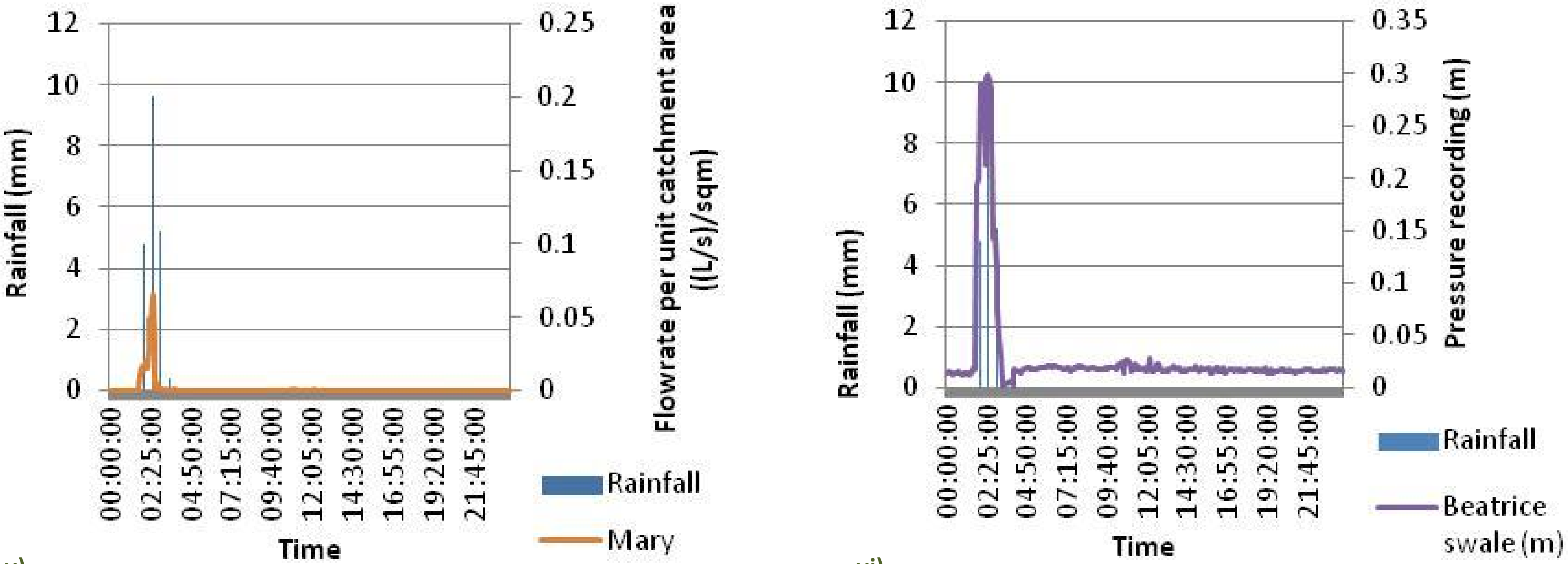




iii)

iv)

Figure 57. (see below)



v)

vi)

Figure 57. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 30th July 2017. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 57.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

Summer event 4 - 22nd July 2017

Figure 58 shows the prevailing weather patterns preceding the rain event on the 22nd July 2017.

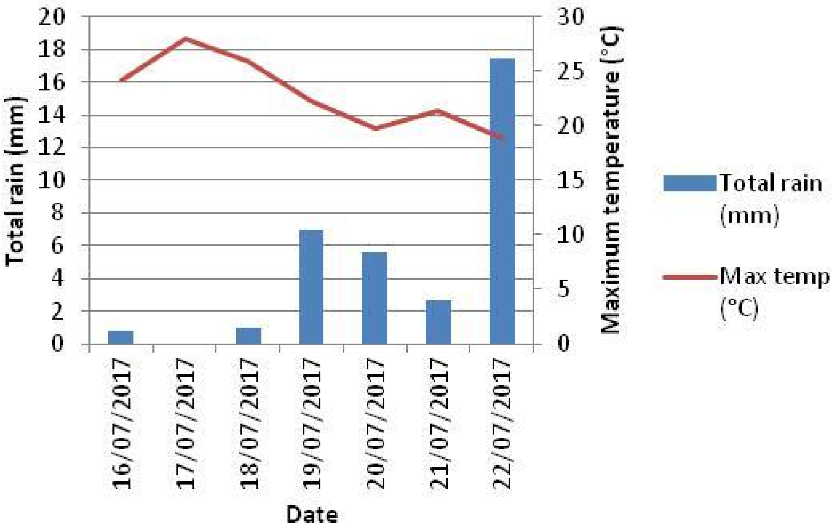


Figure 58. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 17.4 mm on 22nd July 2017.

Table 19 contains the attenuation performance of the pramshed roofs during the rain event on the 22nd July 2017.

Table 19. Pramshed green roof water attenuation performance during a rain event on the 22nd July 2017. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	17.4	22	382.8	84
Charlotte	17.4	32	556.8	76
Mary	17.4	33.5	578.6	87
Average				**82**

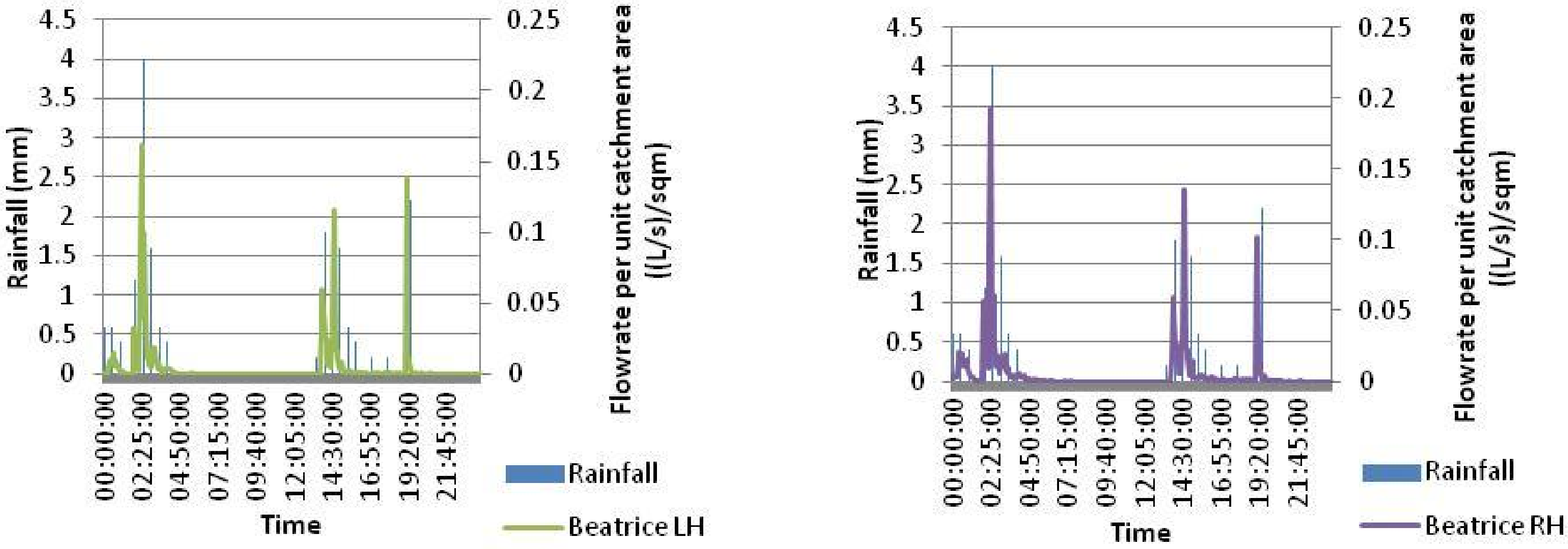
Figure 59 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline Estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial attenuation and reductions in the peak flows from the green roofs compared to the control roofs (Table 59.i). Maximum peak flow reduction recorded was 82%. Peak flows were delayed (Table 59.ii), with the maximum delay being 12 hours and 15 minutes. Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 20. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 17.4 mm rain event on the 22nd July 2017 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	78.73%	67.67%	77.28%
Beatrice RH	82.08%	72.77%	80.86%

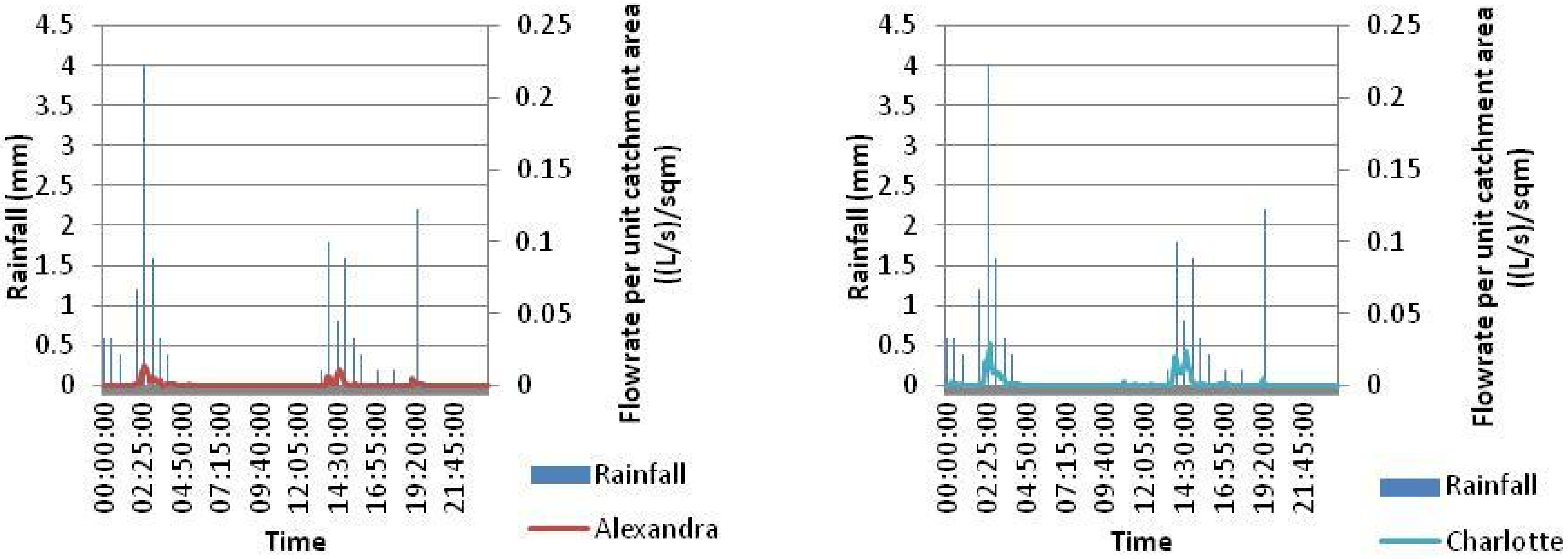
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	00:10:00	00:15:00	12:15:00
Beatrice RH	00:10:00	00:15:00	12:15:00



i)

ii)

Figure 59. (see below)



iii)

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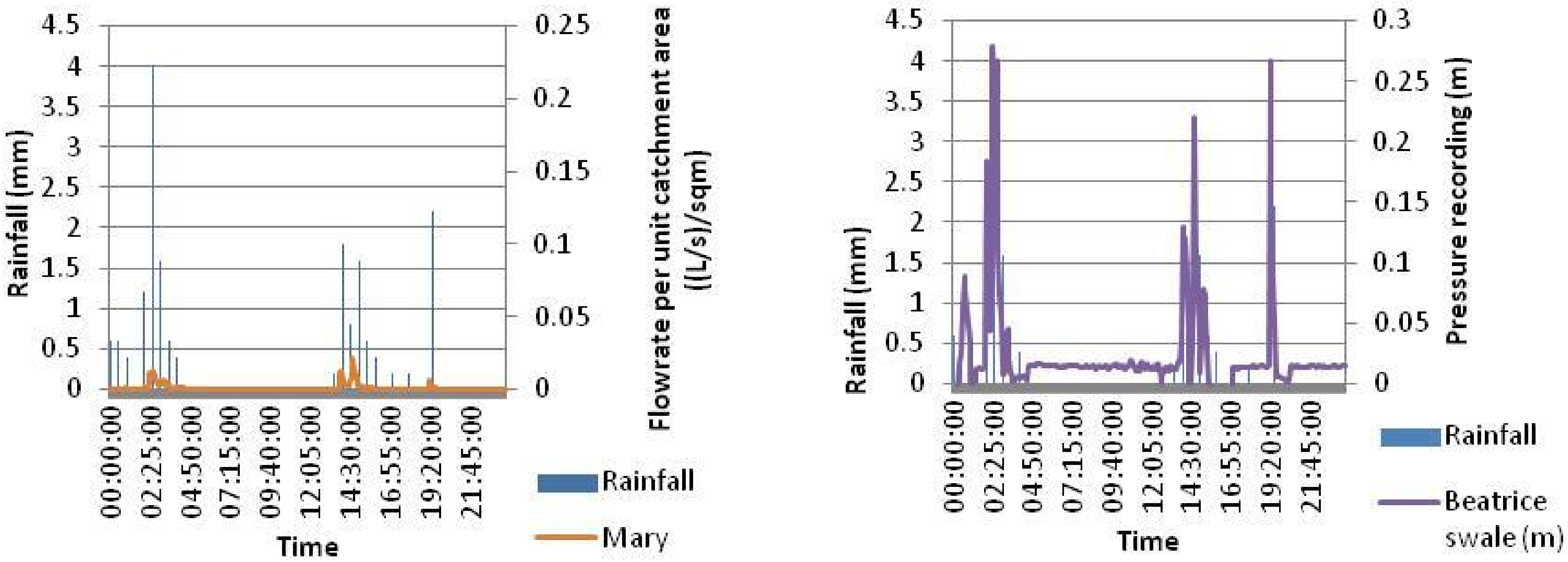
Figure 59. (see below)



v)

vi)

Figure 59. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 22nd July 2017. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 59.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

Summer event 5 - 11th/12th July 2017

Figure 60 shows the prevailing weather patterns preceding the rain event on the 11th/12th July 2017.

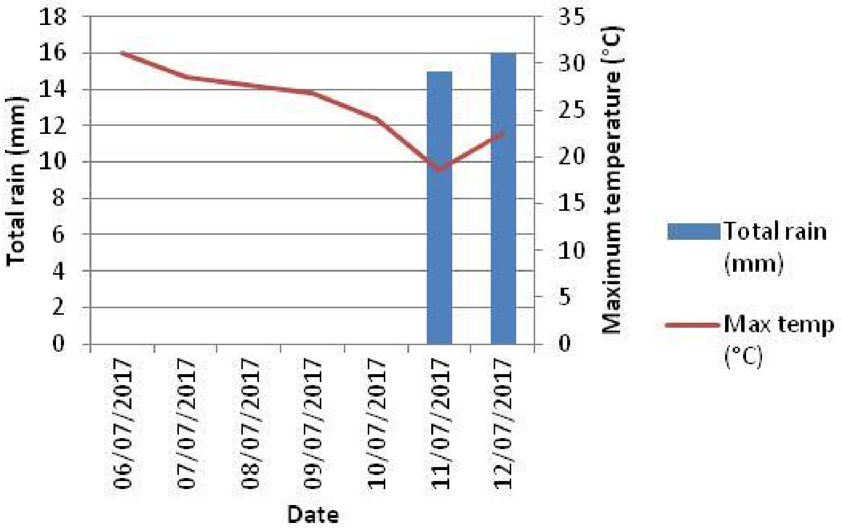


Figure 60. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 31 mm on 11th/12th July 2017.

Table 21 contains the attenuation performance of the pramshed roofs during the rain event on the 11th/12th July 2017.

Table 21. Pramshed green roof water attenuation performance during a rain event on the 11th/12th July 2017. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	31	22	682	90
Charlotte	31	32	992	92
Mary	31	33.5	1030.8	89
Average				**90**

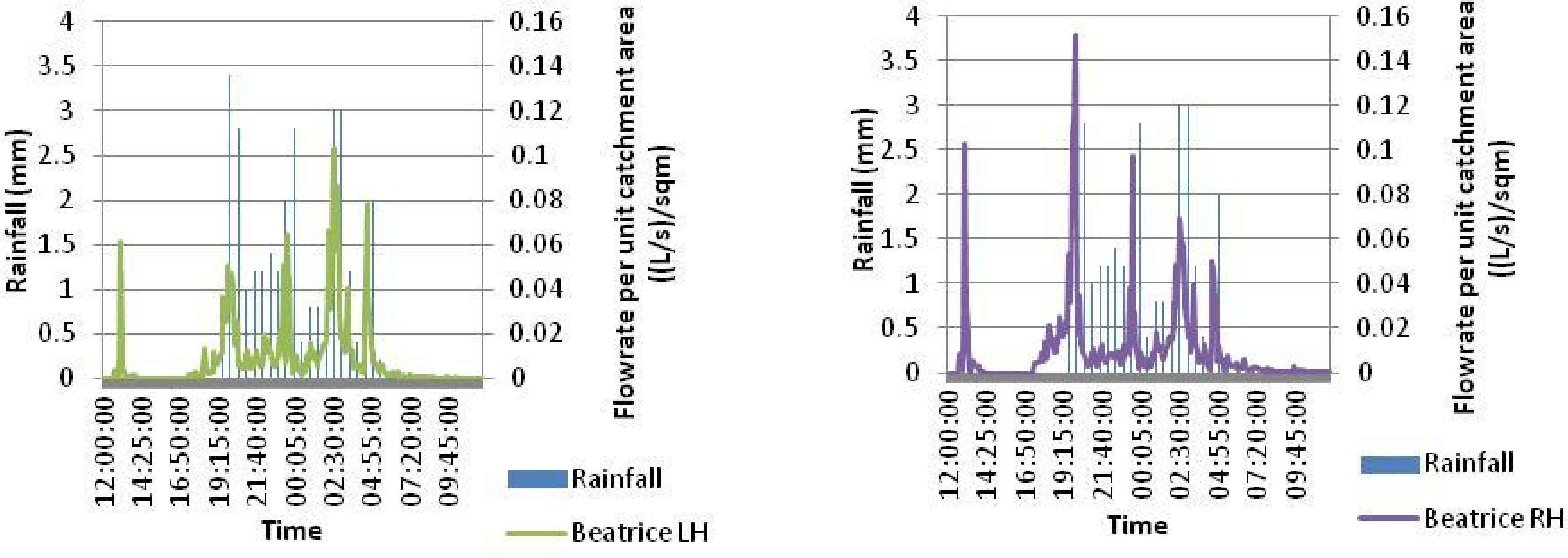
Figure 61 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline Estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial attenuation and reductions in the peak flows from the green roofs compared to the control roofs (Table 22.i). Maximum peak flow reduction recorded was 83%. Peak flows were delayed (Table 22.ii), with the maximum delay being 6 hours and 45 minutes. Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 22. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 31 mm rain event on the 11th/12th July 2017 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	65.50%	75.61%	66.06%
Beatrice RH	76.57%	83.43%	76.94%

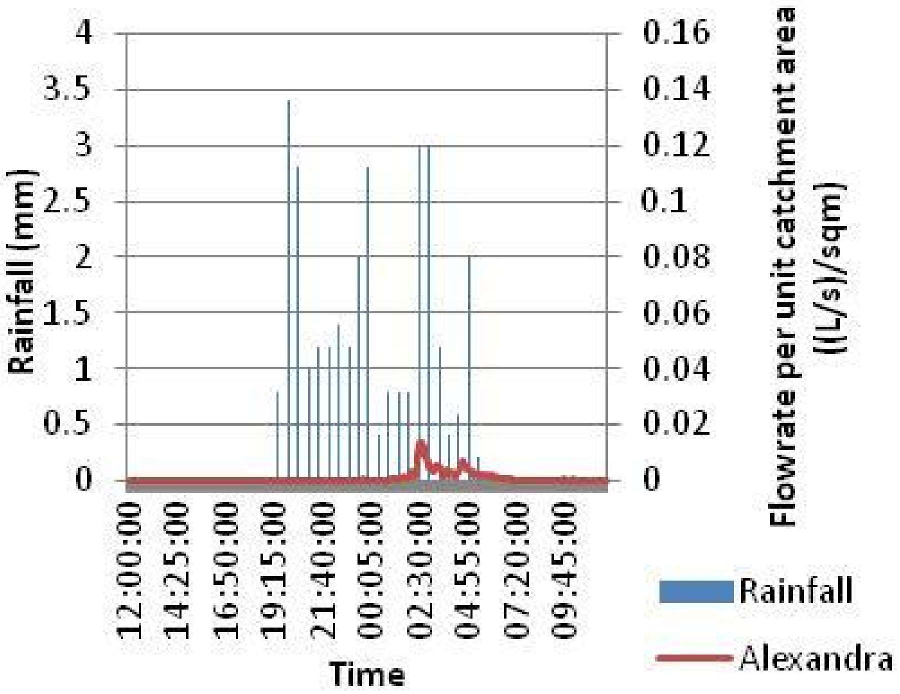
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	00:10:00	00:15:00	00:15:00
Beatrice RH	06:40:00	06:45:00	06:45:00



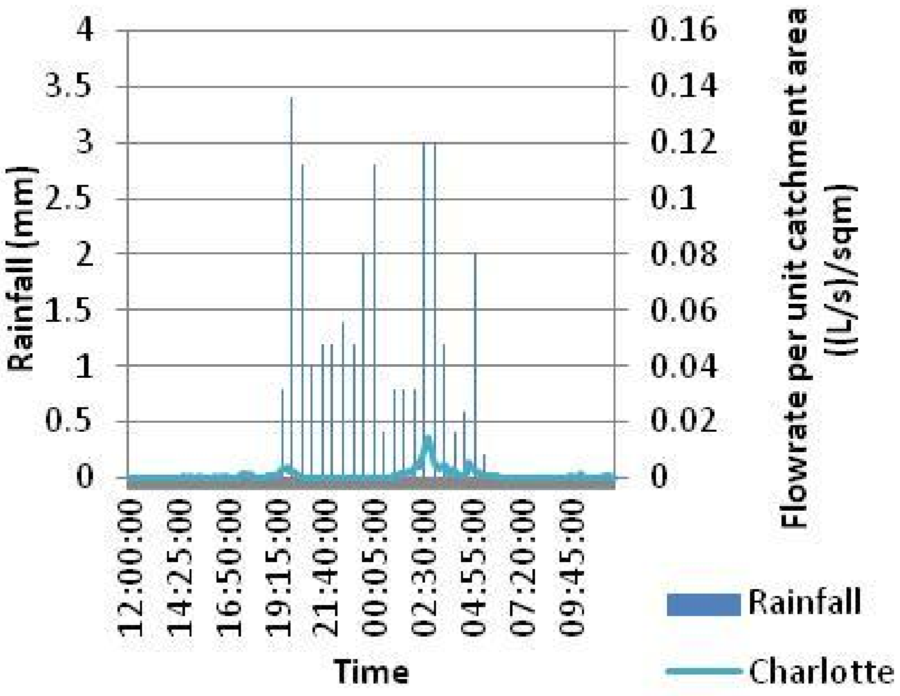
i)

ii)

Figure 61. (see below)

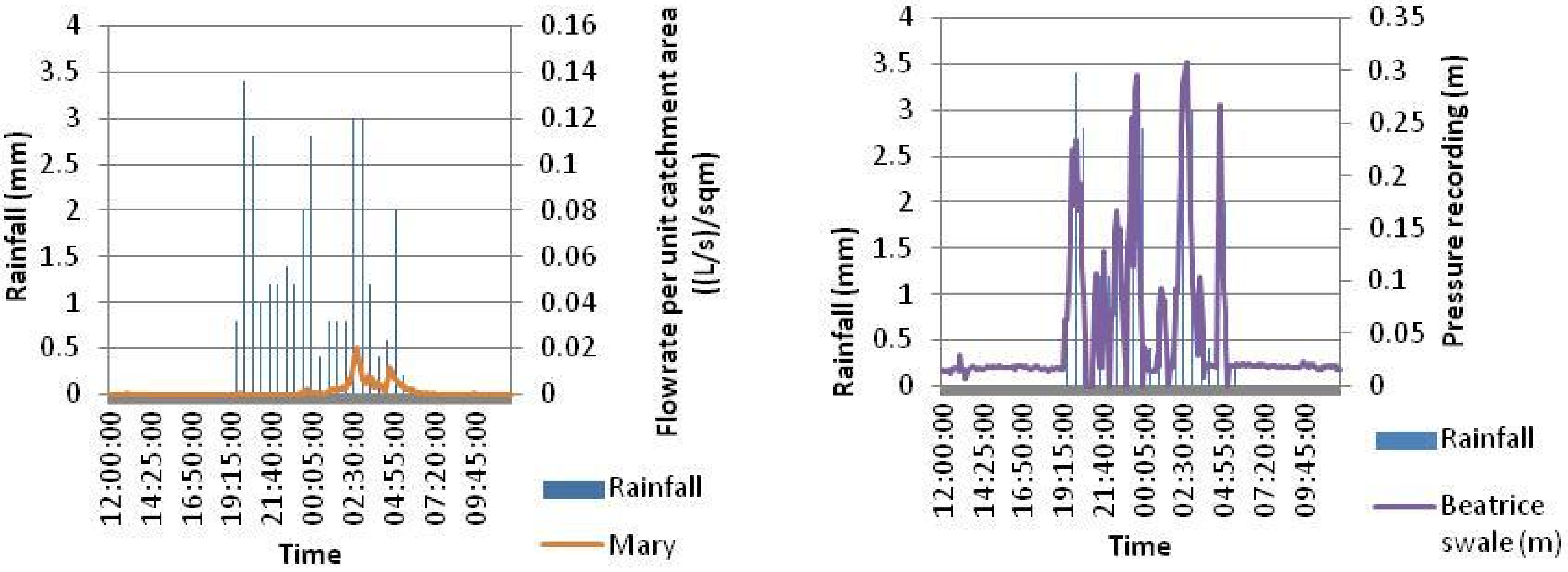


iii)



iv)

Figure 61. (see below)



v) vi)

Figure 61. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 11th/12th July 2017. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre squared to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 61.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

Summer events summary

Data from the five largest summer events indicated that the SuDS systems being monitored were continuing to perform as designed. Beatrice swale received substantial volumes of rainfall during these events and, during all of the summer events, rainfall entering the swale appeared to infiltrate rapidly following the cessation of the each period of rainfall This occurred for all magnitudes and intensities of natural rain events monitored.

The pramshed roofs continued to absorb the majority of the rain that fell onto them. This was quantified in terms of substantial reductions in overall run off and peak flow, and delays in peak flow. In terms of overall reduction in stormwater runoff (compared to the total rainfall on the roof areas), attenuation ranged from a maximum of 95% to a minimum of 62%. Reduction in peak flow ranged from a maximum of 83% to a minimum of 11%. Peak flow rates were delayed by as much as 16 hours. Under the rare occurrence that peak flow occurred earlier from the green roofs than the control roof, peak flow reductions were substantial.

Summary of Queen Caroline Estate SuDS data

It is difficult to compare performance between summer and winter events due to the difference in magnitude, intensity and pattern of the events during each period. However, comparing best and worst performance revealed similar patterns for both periods. Minimum attenuation in winter was slightly lower than in summer as would be expected due to the colder damper weather making it more likely that the roofs would remain more saturated for longer. However, maximum performances were similar.

3.4 Storm event simulations

During the previous monitoring periods, two of the SuDS green infrastructure components installed were tested under simulated storm conditions to assess their performance during the maximum scale of event for which they were designed. These simulations were run at the Beatrice House swale and the Cheeseman Terrace rain gardens (Connop et al. 2016). Both of these events were carried out during summer when the ground would be expected to be relatively dry and the underlying water table low. As such, it would be expected that this would be the period when the SuDS components performed optimally. However, only assessing performance under these conditions would not give a complete overview of their performance potential. This is because summer and winter performance of green infrastructure SuDS components can be very different (Connop et al. 2015). In order to understand their comparative winter performance, when the underlying substrate would be more saturated and the water table higher, a second storm simulation was carried out on each feature during the winter months.

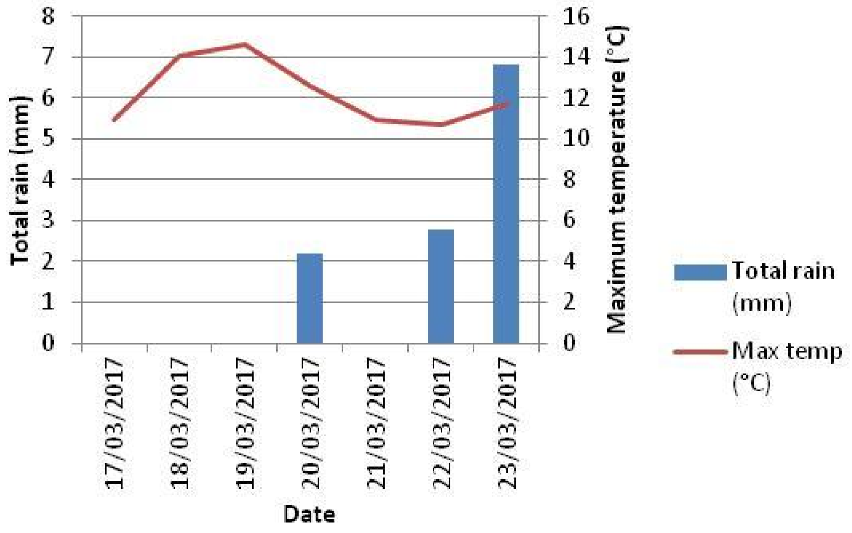
Beatrice House Swale winter conditions rain simulation - 23rd March 2017

On the 23trd March 2017, SRI researchers ran a storm simulation at the Beatrice House swale at Queen Caroline Estate. Beatrice House swale was designed to retain and attenuate a 1 in 100 year storm event for a 250 m^2 catchment area. Based on calculations for the London area, a 1 in 100 rain event would correspond to a 40 mm rain event falling over the period of an hour (Alves et al. 2014).

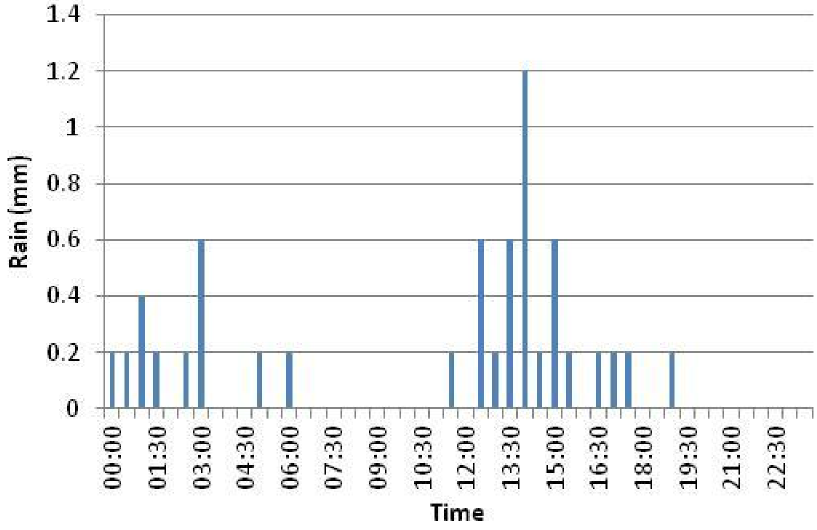
In order to create a simulation of a 1 in 100 year event it was therefore necessary to pump 10,000 L of water into the swale over the course of an hour. In order to achieve this it was necessary to hire a tanker capable of transporting and delivering such a quantity of water (Figure 62). The tanker was hired from BPMcKeefry Ltd.

Figure 62. Water tanker delivering 10,000 Litres of non-potable water for the storm simulation event at Beatrice House swale. Storm simulation was carried out over the course of an hour on the 23rd March 2017.

The tanker water level was calibrated into 1,000 litre divisions and one of these divisions was released into the swale every six minutes over the course of an hour. As much as possible, this release was controlled to be spread across the six minute period, but with no control rate on the water release it was impossible to be entirely accurate with this. Nevertheless, real storms would not be expected to have exactly even rainfall over a storm event, so it was determined that the method adopted would be sufficiently accurate to test the performance of the swale during a 1 in 100 year rain event. Figure 63.i represents the prevailing weather in the 6 days preceding the storm simulation event. Rain events were recorded on two days preceding the rain simulation and on the morning of the simulation prior to its initiation (Figure 63.ii). These events were >2 mm with cool daily temperatures, so it was likely that the underlying substrate would have been more damp than for the summer test. As such, the swale was considered to be in a winter wet state with a higher soil saturation and groundwater table at the time of the storm simulation.



i)



ii)

Figure 63. Weather conditions at Queen Caroline Estate, London Borough of Hammersmith and Fulham, i) on the six days preceding the storm event simulation and ii) on the day of the storm event at Beatrice House swale, 23rd March 2017.

In order to monitor the performance of the swale under the storm simulation conditions, several monitoring techniques were utilised. This included:

- Photographic documentation to show how the basin filled;
- Visual monitoring of the control flow chamber to check for overflow from the swale;
- Pressure sensor data to monitor water infill and infiltration from the swale to assess emptying times following the storm.

Photographs documenting the storm simulation process are presented in Figures 64 to 66.

Figure 64. Images from the storm simulation event at Beatrice House swale, Queen Caroline Estate, 23rd March 2017. Images show i) water release from tanker being timed to release 1000 Litres every six minutes; ii) 1000 Litres entering the centre of the swale; iii) the condition of the swale after the first 1000 Litres.

Figure 65. Images from the storm simulation event at Beatrice House swale, Queen Caroline Estate, 23rd March 2017. Images show that no water was released to the i) swale overflow or ii) the control flow chamber, after the 10,000 Litres of water were pumped into the swale to simulate a 1 in 100 year storm event.

Figure 66. Images from the storm simulation event at Beatrice House swale, Queen Caroline Estate, 23rd March 2017. Images show i) the Beatrice House swale immediately after the last of the 10,000 Litres of water was released and ii) the centre of the swale where the water was pumped in 10 minutes after the last of the water was released.

Using visual monitoring of the swale during the storm simulation event, it was possible to confirm that the Beatrice House swale was able to retain all of the 10,000 Litres of stormwater that was pumped into the basin. Moreover, at no point during the storm simulation did water pooling in the swale reach the swale's stormwater overflow. This was evidenced with the photographs taken during the simulation. From observation, however, it was apparent that water pooled to a much greater extent than during the summer rain simulation event. This difference was also apparent from the photographs (Connop et al. 2106) This result indicated that, during wet winter periods, infiltration was slower than during the summer simulation. Nevertheless, the swale had additional storage capacity that could be used. That could include additional capacity so that a storm greater than a 1 in 100 year event could be retained, or that additional catchment area could be diverted into the existing swale for retention of a 1 in 100 year 1 hour rain event.

In addition to retaining all of the 10,000 Litres of the storm simulation, it is also important to assess how long the water sat in the swale after the event and thus how long until the swale was empty again and the recharge volume available for another storm event. It has been suggested that London soils may be inappropriate for infiltration SuDS components as London soils are generally designated as being heavy impermeable clay and thus do not allow infiltration (Alvez et al 2014). Monitoring how long it takes for any standing water to disappear from the swale after the testing provided a good assessment of infiltration times during the event (although it is not possible to establish whether this was due to basal infiltration or lateral infiltration). Visual assessment of the swale following the study indicated that no standing water was visible within the swale 15 minutes after the storm event. This visual evidence was supported by data obtained from the pressure sensor buried at the base of Beatrice House swale (Figure 67).

Following the initiation of the first 1000 L of the storm event, the levelogger recorded no additional pressure above the baseline level. This may have been indicative of a delay between the infilling of the swale and the water infiltrating to the levelogger, or may have indicated that all of the initial storm simulation water infiltrated very quickly before saturation resulted in pooling. This pattern was the same as was recorded during the summer rain simulation. By the time that the second 1000 L of water had been pumped into the swale, the water level had increased indicating that pooling/soil saturation was occurring. Following the cessation of the storm simulation (i.e. after all 10,000 L had been pumped into the swale), the levelogger indicated that pooling disappeared very rapidly - within 10 minutes of the end of pumping the pressure readings had returned to the pre-testing baseline level. This data supported observations made on site and indicated that infiltration rates were fast. This provided evidence that recharge volumes would be available very quickly following a 1 in 100 year storm event during winter conditions. This mimicked the results recorded during the summer simulation. Whilst there was greater pooling during this winter event and the time for the levelogger pressure to return to the baseline level following the cessation of the storm event was slightly longer, this was still very rapid and indicated that the swale was easily able to cope with 1 in 100 year storm events for the current catchment area.

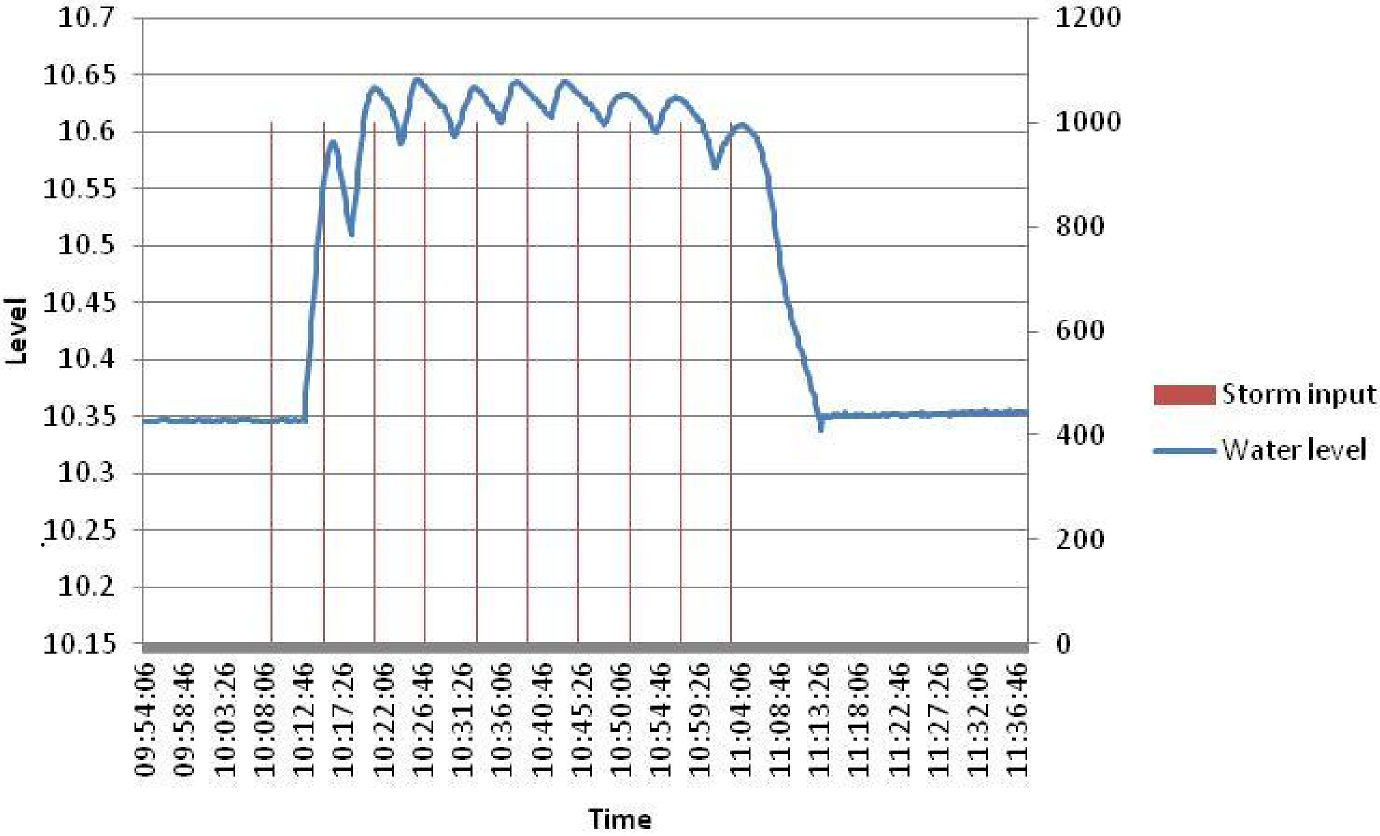


Figure 67. Pressure sensor data from 1 in 100 year storm simulation event at Beatrice House swale, Queen Caroline Estate, London Borough of Hammersmith and Fulham. Blue bars represent the times when stormwater was pumped into the swale, the red line represents the readings of a pressure sensor buried beneath the swale to monitor pooling water.

Summary - Key points of interest

i) Input of the first 1,000 L of storm water was not detected by the pressure sensor. This was presumably because the pressure sensor is offset to the side of centre of the swale (next to the westernmost downpipe) and it took till the second 1000 L input for the water to reach the pressure sensor.

ii) Despite the weather preceding the stimulation being wet (including the morning of the simulation) and temperatures being cool and thus evaporation rates being low, evidence of infiltration was recorded between each 1000 L stormwater input.

iii) Water pooling observed during the test was more obvious that during the previous summer testing.

iv) Nevertheless, all evidence of standing water within the swale had disappeared within 15 minutes of the end of the simulation.
iiv) This observational evidence was supported by the pressure sensor levels which had returned to pre-testing levels within 10 minutes following the cessation of the storm event.
iiiv) Beatrice House Swale had the capacity to deal with 1 in 100 year 1 hour rain events both during periods of high evapotranspiration and during periods of low evapotranspiration.

Sun Road Rain Garden , Cheeseman Terrace - 24th March 2017

On the 24th March 2017, SRI researchers ran a storm simulation at the Sun Road rain gardens at the Cheeseman Terrace Estate. The rain gardens were designed to retain and attenuate a 1 in 2 year storm event for a 310 m² catchment area. Due to the success of the Beatrice swale test and the design of the rain gardens permitting excess stormwater to overflow to storm drains, the rain garden was tested under 1 in 5 year storm condition during the previous summer (Connop et al. 2016). This test was successful, so a 1 in 5 year storm event simulation was also run for the winter test. This corresponded to a 18 mm rain event falling over the period of an hour.

In order to create this simulation of a 1 in 5 year event, it was therefore necessary to pump 5580 L of water into the swale over the course of an hour. In order to achieve this it was necessary to hire a tanker capable of transporting and delivering such a quantity of water (Figure 68). The tanker was hired from BPMcKeefry Ltd.

The tanker water level was calibrated into 1,000 litre divisions and one of these divisions was released into the rain gardens every ten minutes over the course of an hour. Each 1000 litres was approximately divided between the inlet chambers of the first and third rain gardens to mimic as closely as possible a natural storm event. The release of flow was controlled using a guillotine. However it was not possible to control the rate of release so water was directed into inspection chambers with only a small proportion of it being released directly onto the surface of the rain gardens as a result of spillage. As much as possible, the release was controlled to be spread across the ten minute period, but with no control rate on the water release it was impossible to be entirely accurate with this. Nevertheless, real storms would not be expected to have exactly even rainfall over an entire storm event, so it was determined that the method adopted would be sufficiently accurate to test the performance of the swale during a 1 in 5 year rain event. Figure 69 represents the prevailing weather in the 6 days preceding the storm simulation event. No rain occurred on the day of the test. There were, however, rain events recorded on three of the four days preceding the rain simulation. These events were all >2 mm. Combined with cool warm daily temperatures, this would mean that the substrate within and beneath the rain gardens would have been likely to be more saturated than during the summer test, thus creating the conditions for a comparative winter rain simulation.

Figure 68. Water tanker delivering 6000 Litres of non-potable water for the storm simulation event at Cheeseman Terrace Estate. A storm simulation was carried out over the course of an hour on the 24th March 2017.

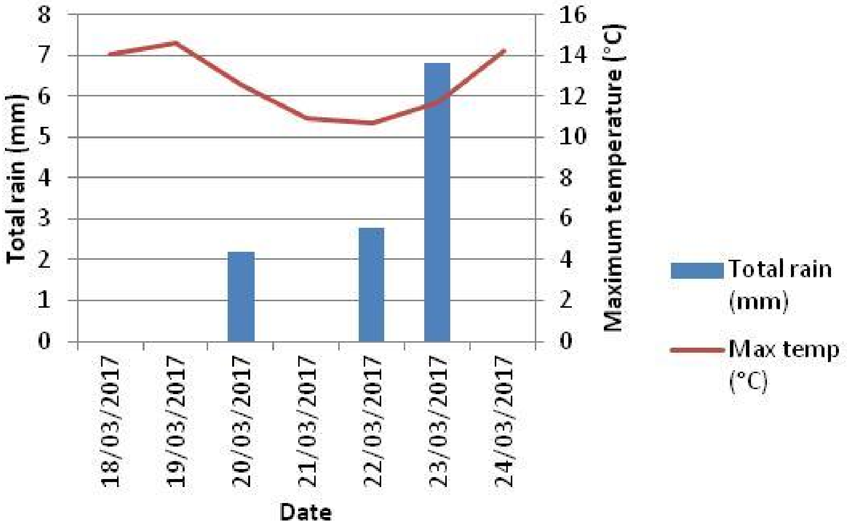


Figure 69. Weather conditions in Hammersmith preceding the storm event simulation at the Cheeseman Terrace Estate rain gardens, 24th March 2017. It was not possible to install a weather station at the Cheeseman Terrace site, due to the lack of availability of a suitable building on which it could be located. As such, data from the nearest weather station, at Henrietta House, Queen Caroline Estate is displayed.

In order to monitor the performance of the swale under the storm simulation conditions, several monitoring techniques were utilised. This included:

- Photographic documentation to show how the rain gardens filled;
- Visual monitoring of the control flow chamber to check for overflow from the rain gardens;
- Pressure sensor data to monitor water infill and infiltration from the rain gardens to assess emptying times following the storm;
- Soil moisture sensor to detect changes in surface level moisture.

Photographs documenting the storm simulation process are presented in Figures 70 to 73.

Figure 70. Images from the storm simulation event at the Sun Road rain gardens, Cheeseman Terrace Estate, 24th March 2017. Images show i) Cheeseman Terrace Estate rain gardens before rain simulation; ii) pressure sensor installed in the control flow chamber in the outlet from the rain garden.

Figure 71. Images from the storm simulation event at the Sun Road rain gardens, Cheeseman Terrace Estate, 24th March 2017. Images show i) water being pumped into the inspection chamber of the rain garden; ii) inlet chamber full after the stormwater was pumped in.

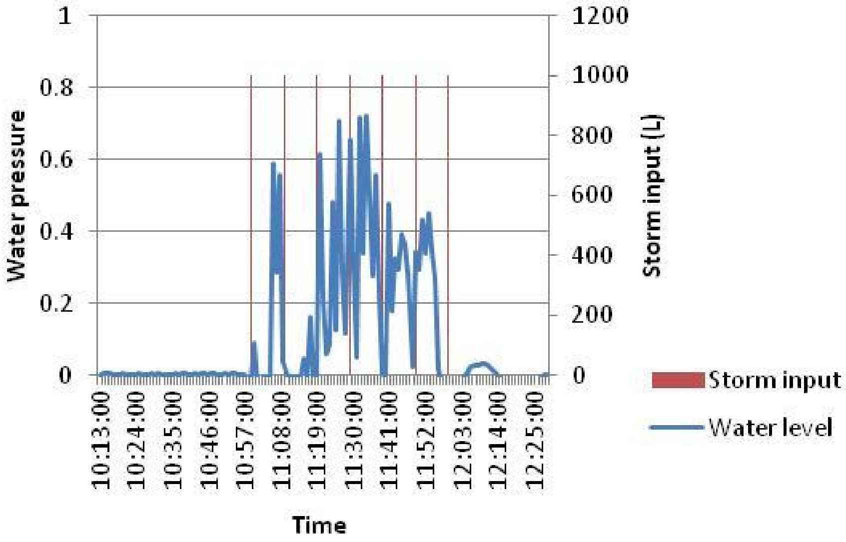
Figure 72. Images from the storm simulation event at the Sun Road rain gardens, Cheeseman Terrace Estate, 24th March 2017. Images show i) the rain garden inspection chamber overflowing onto the rain garden during the rain simulation and ii) the control flow chamber releasing water from the rain gardens following the 1 in 5 year storm event simulation.

Figure 73. Image from the storm simulation event at the Sun Road rain gardens, Cheeseman Terrace Estate, 27th March 2017. Image shows the stormwater that was released from the rain garden overflow being released to the combined sewer system during the final 1000 L release of the stormwater simulation test.

Using visual monitoring of the rain gardens during the storm simulation event, it was possible to confirm that the Cheeseman Terrace rain gardens were not able to retain all of the 6,000 Litres of stormwater that was pumped into the inspection chambers. Whilst this was not necessarily a surprise, as the rain garden was designed to cope with a 1 in 2 event, it did not mirror the results from summer test where all of the storm event was retained. This indicated a difference in performance between the summer and winter periods, presumably linked to the substrate within and beneath the rain gardens being more saturated during the winter rain event. This exceedance of capacity was evidenced with the photographs taken during the simulation. This included a filling and overflowing of water within the inspection chambers, water being released through the overflow chamber and water entering the storm sewer system. Water was also observed backing up through the under-road drainage channels and overflowing from the roadside storm drains. This indicated that the rate stormwater was introduced exceeded the ability of the rain garden system to convey water to the overflow chamber. This may, however, have been the result of the method of introducing the water to the rain garden through rapid bursts, rather than evenly throughout the hour period. Nevertheless, the water level in the inspection chambers dropped following the cessation of the storm simulation and within an hour of the end of the simulation, levels had almost returned to those prior to the running of the simulation.

In addition to visually monitoring the 6000 Litres of the storm simulation, it is also important to assess how long this water sits in the rain gardens after the event and thus how long until the rain gardens are empty again and the recharge volume is available for another storm event. It has been suggested that London soils may be inappropriate for infiltration SuDS components as London soils are generally designated as being heavy impermeable clay and thus do not allow infiltration (Alvez et al 2014). Monitoring how long it takes for any standing water to disappear from the rain garden after the testing provided a good assessment of infiltration times during the event (although it is not possible to establish whether this was due to basal infiltration or lateral infiltration). Visual assessment of the rain gardens following the study indicated that little standing water was visible within the rain garden inspection chambers 2 hours and 30 minutes after the storm event.

Figure 74 represents the pressure sensor data from the series of pressure loggers situated throughout the rain garden complex at Sun Road, Cheeseman Terrace. The southernmost (PS2) and northern most gauges (PS4) were situated in the drainage pipes at the bottom of the inspection chambers immediately within the rain gardens where the road runoff gullies enter the base of the rain gardens. The middle gauge (PS3) was buried in the substrate of the rain garden between the other two rain gardens. The outlet gauge (PS5) was situated before the weir in the controlled outflow chamber that links the rain garden drainage pipes to the combined sewer system. The data provides a comprehensive representation of the performance of the rain gardens during the 1 in 5 year 1 hour summer storm event on the swale.



i)

Figure 74 (see below)

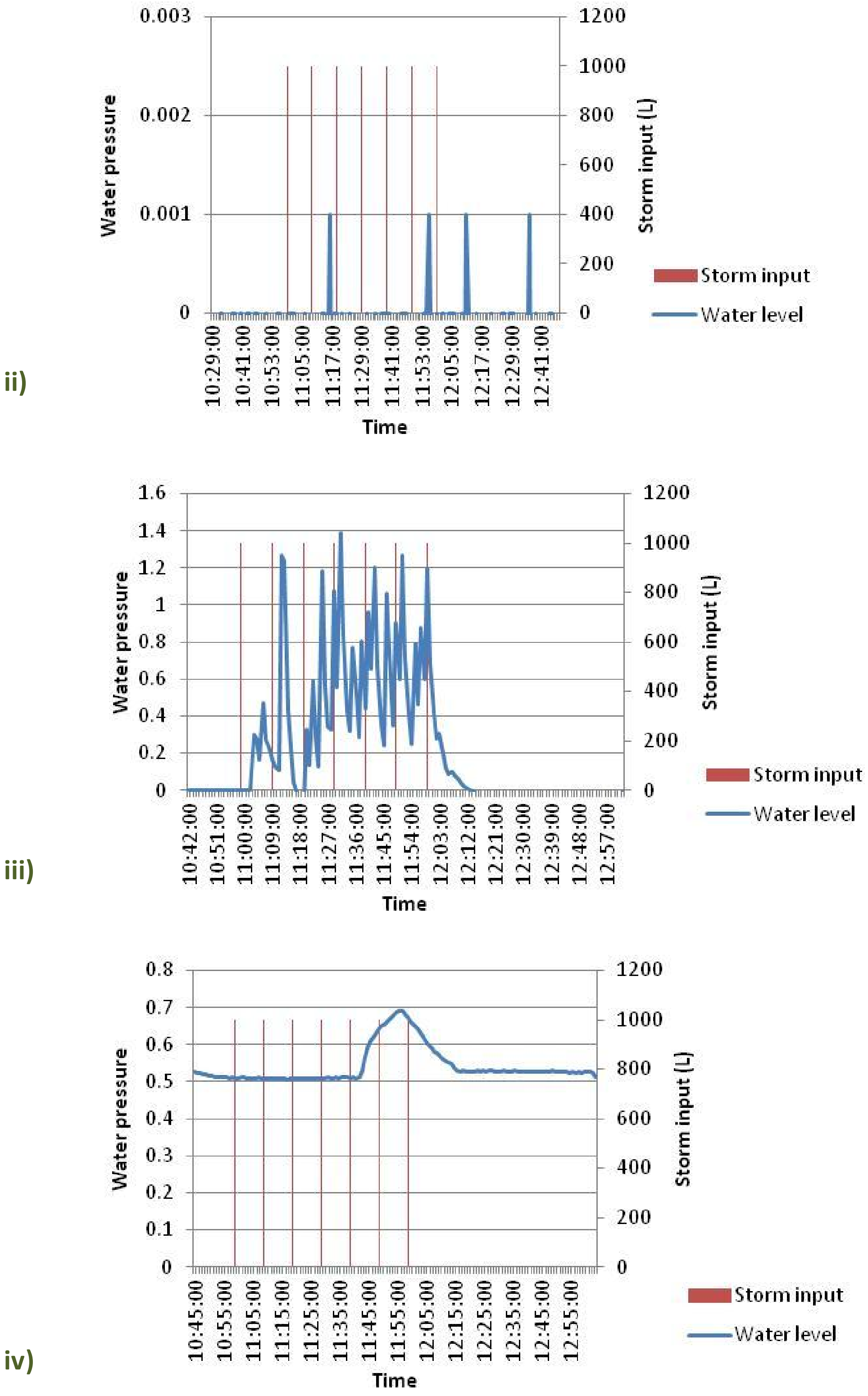


Figure 74. Pressure sensor data from the storm event at Sun Road Rain Gardens, 24th March 2017. A 1 in 5 year 1 hour storm event simulated to assess rain garden performance. The graphs represent i) a pressure sensor in the drainage channel at the base of the southernmost rain garden (FS2); ii) a pressure sensor in the substrate of the middle rain garden (FS3); iii) a pressure sensor in the drainage channel at the base of the northernmost rain garden (FS4); iv) a pressure sensor in the weir in the controlled outflow chamber that links the rain garden drainage pipes to the combined sewer system (FS5).

Summary - Key points of interest

- As expected, the gauges in the drainage channel were very reactive to the stormwater input. This was due to the stormwater being introduced directly into these areas to avoid damage to the new planting.
- The method of introduction of storm water was not entirely representative of a natural storm event as a greater proportion of the rainfall would go directly onto the surface of the rain gardens during a natural event. Whilst a small volume did during this method, the majority of this was in the northern and southern rain gardens due to overflow whilst filling. This was reflected in the results for the middle rain garden which recorded some changes in pressure but relatively little. This indicated that there was little lateral movement of water from the perforated drainage channels beneath the connected rain gardens to the substrate of the central rain garden. This is a different result to that recorded during major natural rain events at Cheeseman Terrace (Section 3.3.1), when a proportion of the rainfall fell directly onto the central rain garden.
- Despite the significant volumes of stormwater introduced via the inspection chamber, there was evidence of infiltration from the rain garden between each stormwater release with levels recorded by pressure sensors PS2, PS3 and PS4 dropping between inputs of stormwater.
- There was visual evidence of the capacity of the drainage channels being exceeded during stormwater introduction. This included the backing up of water under the road and out of the roadside storm drains and water levels rising within the inspection chambers until they over-topped the chambers onto the rain gardens.
- After approximately 5000 L of stormwater input, the control flow chamber began to fill and a controlled flow rate was released into the combined sewer system. The water level in the control flow chamber did not rise to a level whereby it came close to over-topping the weir. However stormwater was observed backing up through the road-under drains.
- Fifteen minutes after the final 1000 L (of the total 6000 L) was released into the rain garden, infiltration had occurred to such an extent that no further release was recorded at the control flow chamber. This observed result was supported by data from pressure sensor PS5 in the control flow chamber which returned to the pre-testing baseline level within 20 minutes of reaching the peak pressure value (Figure 74).
- Fifteen minutes after the final 1000 L was released there was also no visible pooling remaining on the surface of the rain gardens.
- Thirty minutes after the final 1000 L was released the level in the inspection chamber of the southernmost rain garden was back to pre-testing levels and the level in the northernmost rain garden had stopped falling but there still remained some water in

the bottom of the inspection chambers. Two and a half hours later this level had dropped further and only a small amount of water still remained in this chamber.

These preliminary results demonstrated that performance was reduced compared to the summer performance for the Sun Road rain gardens. Nevertheless, the rain gardens were able to cope with all of the water introduced to the system and only released a small volume for a 30 minute period during and after the event. The capacity of the control flow chamber was never at risk of being over-topped. Thus stormwater was released at a controlled rate and water release at a rate that would have occurred were there no rain garden feature at the site did not occur. As such, the data indicated that the Sun Road rain gardens have the capacity to deal with 1 in 5 year 1 hour rain events both during periods of high evapotranspiration and during periods of low evapotranspiration.

3.5 Thermal monitoring

Thermal camera images taken using a FLIR B335 thermal imaging camera were analysed using FLIR Tools© software to assess temperature differences between green infrastructure retrofit features, pre-existing green infrastructure features and hardstanding areas across Queen Caroline Estate and Richard Knight House and surrounding areas.

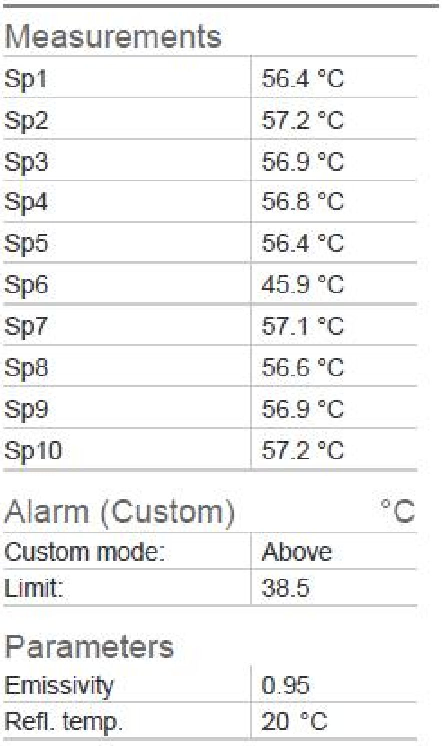
Visits were made on several hot days during the second monitoring period. This included the 14th June and 21st June 2017. Maximum temperatures recorded at the Queen Caroline Estate weather station on these days were 26.3°C and 33.1 °C respectively. Maximum temperatures recorded at the Richard Knight House weather station were 26.8°C and 34.1°C respectively.

Results for these hot days when site visits were made with the thermal imaging camera are presented below. Results are broken down by date.

Thermal imaging 14th June 2017

Location: Richard Knight House

This date coincided with a green roof survey at RKH so thermal pictures were taken at roof level of the green infrastructure elements below.



Measurements

Sp1	56.4 °C
Sp2	57.2 °C
Sp3	56.9 °C
Sp4	56.8 °C
Sp5	56.4 °C
Sp6	45.9 °C
Sp7	57.1 °C
Sp8	56.6 °C
Sp9	56.9 °C
Sp10	57.2 °C

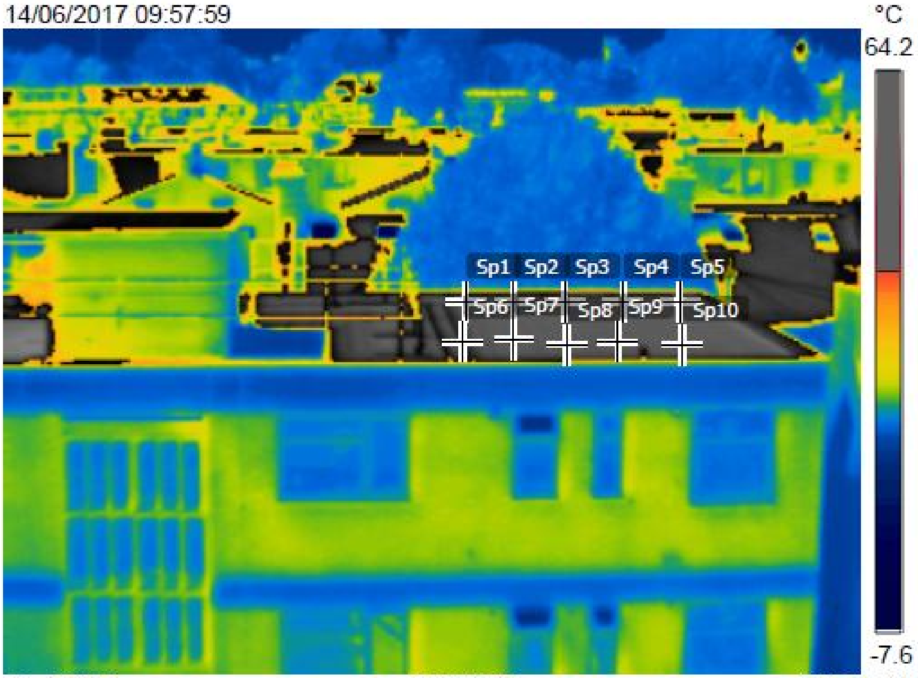
Alarm (Custom) °C

Custom mode:	Above
Limit:	38.5

Parameters

Emissivity	0.95
Refl. temp.	20 °C

14/06/2017 09:57:59



IR_1360.jpg FLIR B335 456003535

14/06/2017 09:57:59

DC_1361.jpg

Figure 75. Photo and infrared image of the control roof and surrounding grey infrastructure at Richard Knight House on the 14th June 2017. FLIR tools software was used to identify temperatures at selected points within the field of view. The hottest temperatures (>45 °C) were associated with the control roof and other surrounding roofs. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (26.3 °C).

Measurements

Sp1	26.4 °C
Sp2	26.7 °C
Sp3	29.9 °C
Sp4	29.1 °C
Sp5	27.6 °C
Sp6	29.8 °C
Sp7	46.0 °C
Sp8	41.0 °C
Sp9	45.5 °C
Sp10	38.7 °C

Alarm (Custom) °C

Custom mode:	Above
Limit:	38.5

Parameters

Emissivity	0.95
Refl. temp.	20 °C

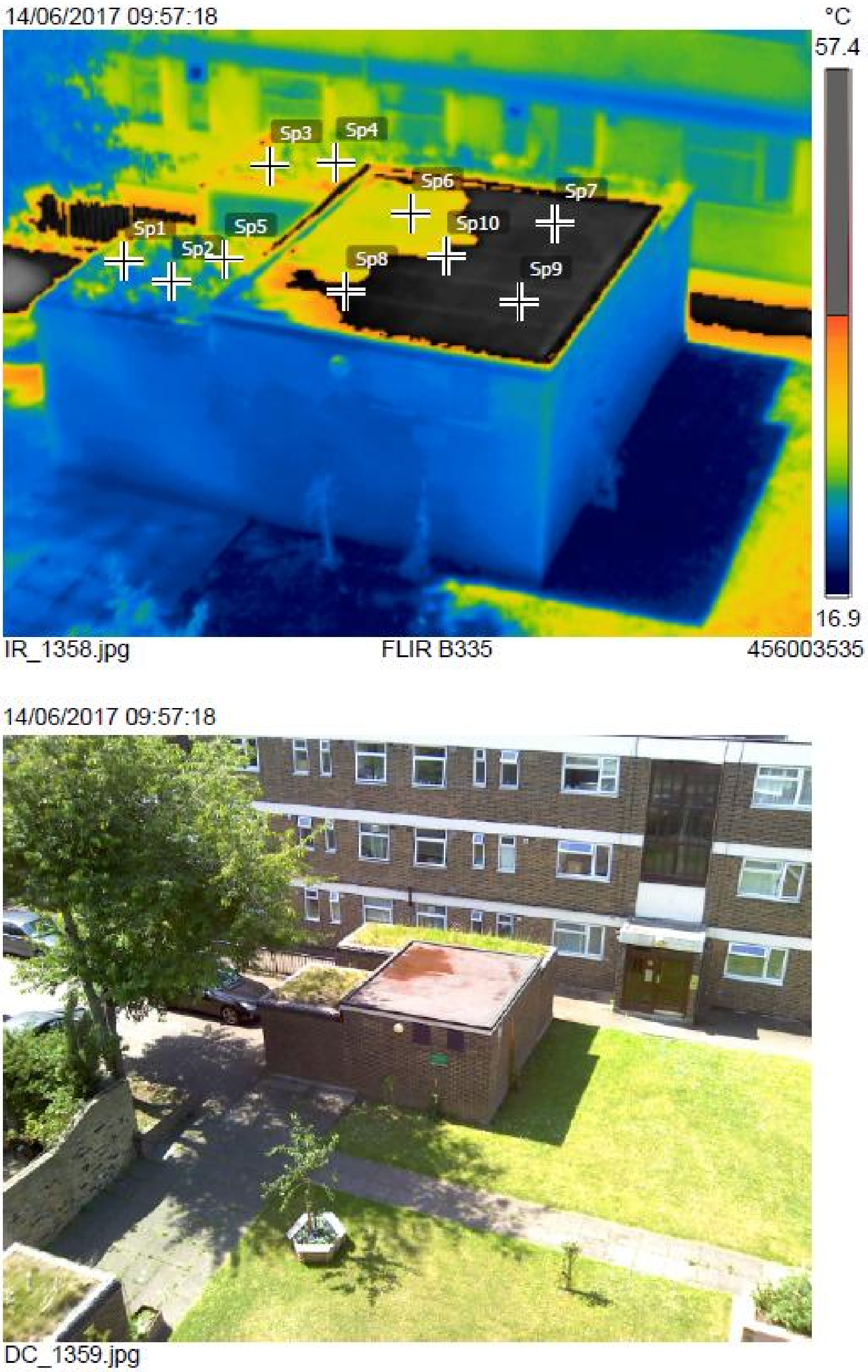


Figure 76. Photo and infrared image of standard pramshed and green roofs at Richard Knight House on the 14th June 2017. FLIR tools software was used to identify temperatures at selected points within the field of view. The hottest temperatures (>40 °C) were associated with the pramshed roof. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (26.3 °C). Temperatures on the pramshed green roofs were substantially lower at <30°C. These temperatures were either lower or similar to the temperature of pooled water on the standard pramshed roof (29.8°C).

Measurements	
Sp1	28.6 °C
Sp2	31.7 °C
Sp3	33.1 °C
Sp4	32.3 °C
Sp5	32.7 °C
Sp6	44.1 °C
Sp7	43.8 °C
Sp8	47.2 °C
Sp9	43.4 °C
Sp10	40.6 °C

Alarm (Custom)	°C
Custom mode:	Above
Limit:	38.5

Parameters	
Emissivity	0.95
Refl. temp.	20 °C

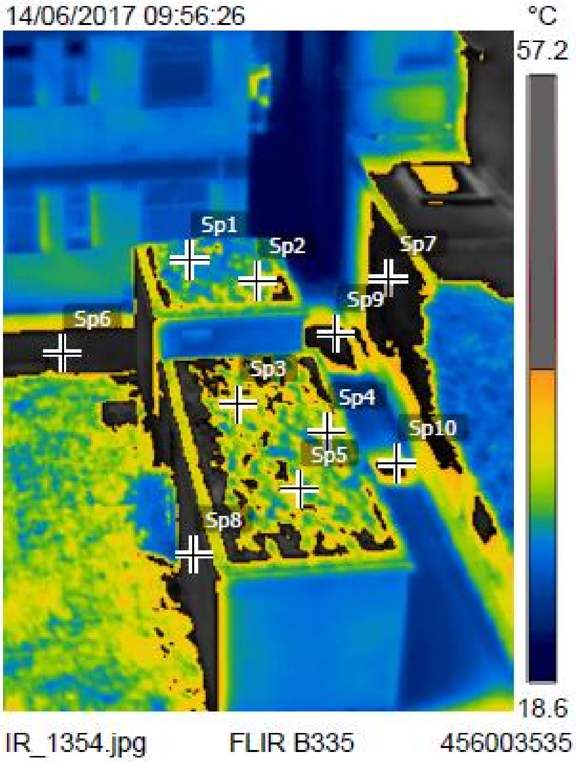


Figure 77. Photo and infrared image of pramshed green roofs at Richard Knight House on the 14th June 2017. FLIR tools software was used to identify temperatures at selected points within the field of view. The hottest temperatures (>40 °C) were associated with the surrounding grey infrastructure. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (26.3 °C). Temperatures on the pramshed green roofs were lower at <35°C.

Measurements

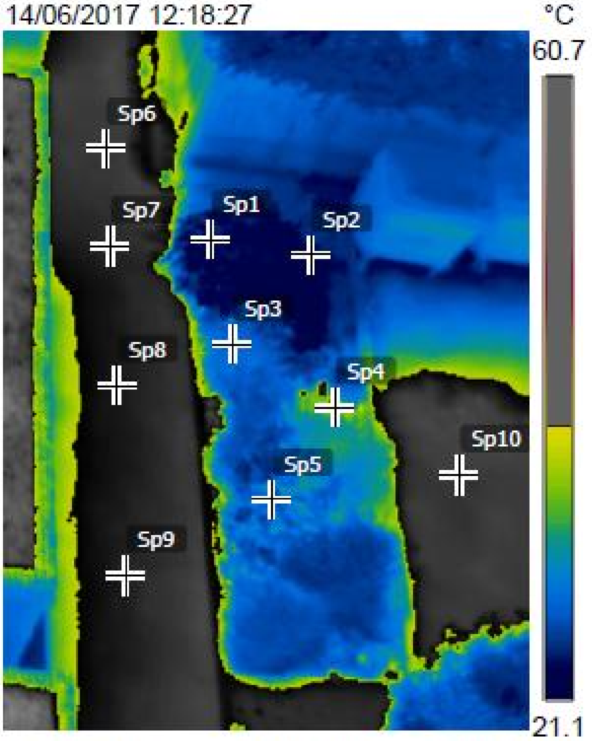
Sp1	23.3 °C
Sp2	22.1 °C
Sp3	28.2 °C
Sp4	36.3 °C
Sp5	27.8 °C
Sp6	48.4 °C
Sp7	45.4 °C
Sp8	42.6 °C
Sp9	44.7 °C
Sp10	48.8 °C

Alarm (Custom)	°C
Custom mode:	Above
Limit:	38.5

Parameters

Emissivity	0.95
Refl. temp.	20 °C

14/06/2017 12:18:27



IR_1386.jpg FLIR B335 456003535

14/06/2017 12:18:27

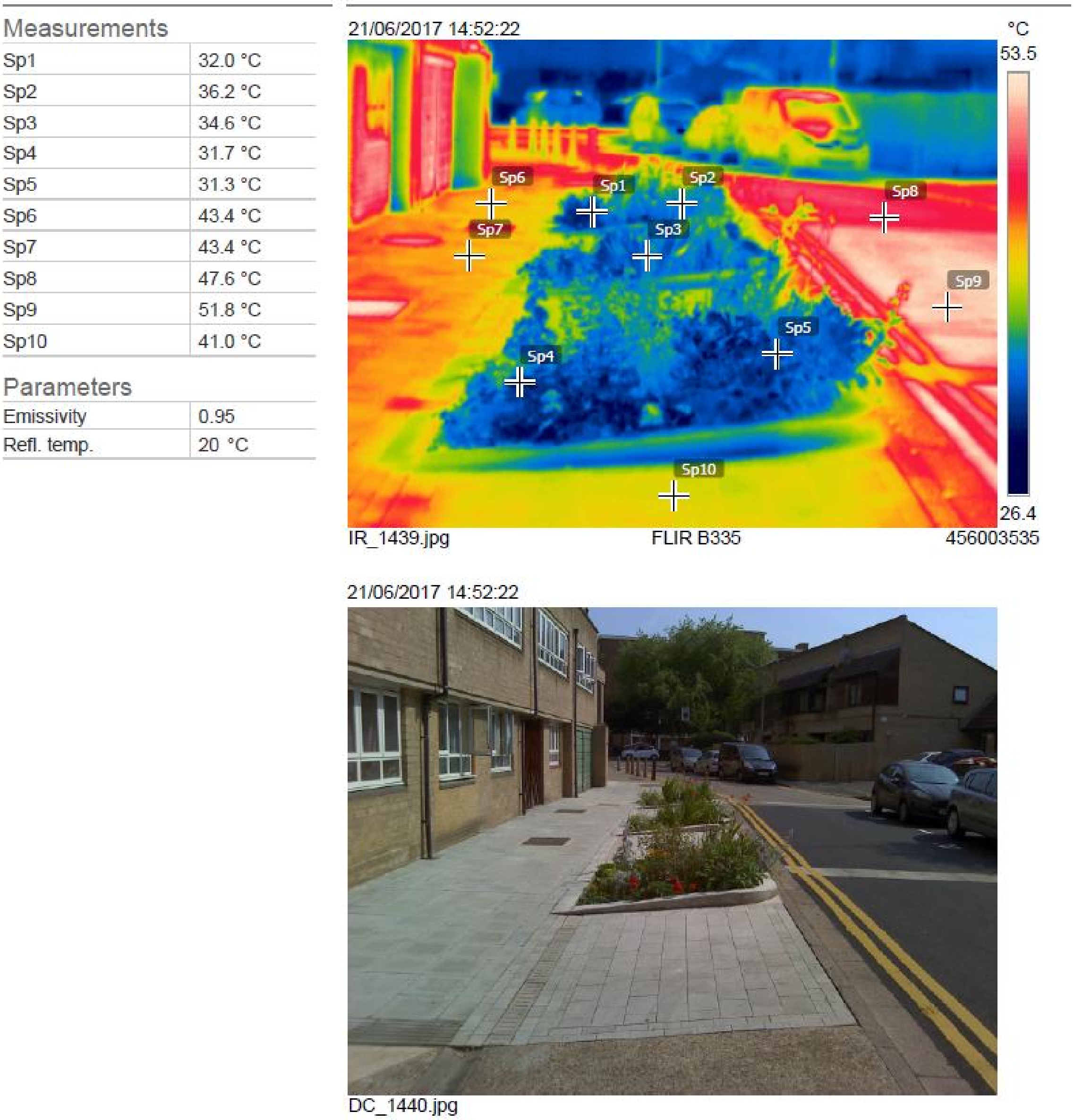
DC_1387.jpg

Figure 78. Photo and infrared image of Richard Knight House rain garden and surrounding grey infrastructure on the 14th June 2017. FLIR tools software was used to identify temperatures at selected points within the field of view. The hottest temperatures (>45 °C) were associated with the surrounding grey infrastructure. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (26.3 °C). Temperatures on the green roofs were lower by at least 6 degrees with all temperatures <36°C.

Thermal imaging 21st June 2017

Location: Cheeseman Terrace and Queen Caroline Estate

This was a hotter day than the 14th June, with 33.1°C to 34.1°C recorded at the Queen Caroline Estate and Richard Knight House weather stations respectively. This trip involved taking images around the above estates from ground and roof level.


Measurements

Sp1	32.0 °C
Sp2	36.2 °C
Sp3	34.6 °C
Sp4	31.7 °C
Sp5	31.3 °C
Sp6	43.4 °C
Sp7	43.4 °C
Sp8	47.6 °C
Sp9	51.8 °C
Sp10	41.0 °C

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Figure 79. Photo and infrared image of Cheesemans terrace rain garden and surrounding grey infrastructure on the 21st June 2017. FLIR tools software was used to identify temperatures at selected points within the field of view. The hottest temperatures (>40 °C) were associated with the surrounding grey infrastructure. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (34.1 °C). Temperatures observed in the rain gardens were lower by at least 5 degrees with all temperatures 36°C or less. The coolest areas were observed in the well-established vegetation (sp4 and sp 5 at 31.7°C and 31.2°C respectively).

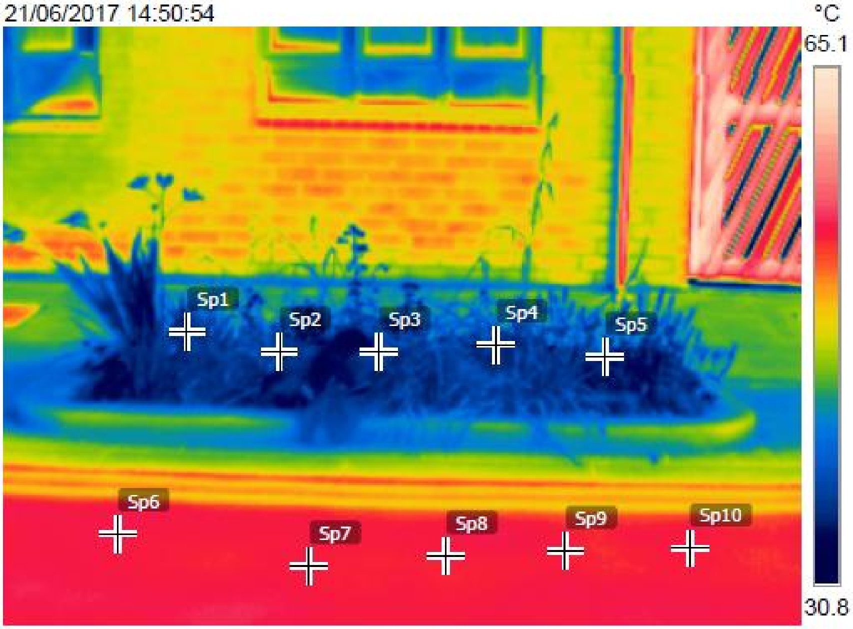
Measurements

Sp1	36.3 °C
Sp2	36.5 °C
Sp3	38.3 °C
Sp4	36.8 °C
Sp5	35.9 °C
Sp6	55.2 °C
Sp7	54.9 °C
Sp8	54.7 °C
Sp9	54.7 °C
Sp10	54.8 °C

Parameters

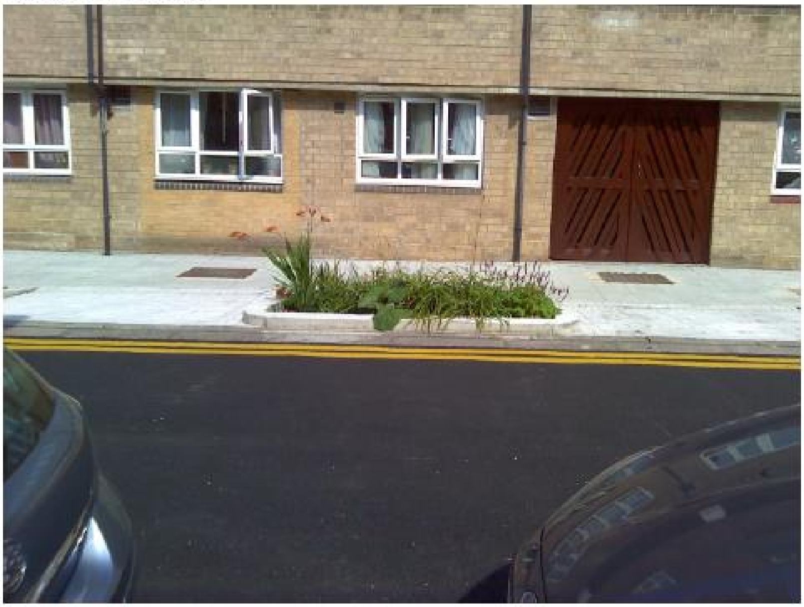
Emissivity	0.95
Refl. temp.	20 °C

21/06/2017 14:50:54



IR_1433.jpg FLIR B335 456003535

21/06/2017 14:50:54



DC_1434.jpg

Figure 80. Photo and infrared image of Cheeseman's terrace rain garden and surrounding grey infrastructure on the 21st June 2017. FLIR tools software was used to identify temperatures at selected points within the field of view. The hottest temperatures (>50 °C) were associated with the newly lain road. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (34.1 °C). Temperatures observed in the rain gardens were lower by almost 20 degrees with all temperatures approximately 38°C or lower. The coolest areas were observed in the well-established vegetation (sp 5 at 35.9°C).

Queen Caroline Estate

Measurements	
Sp1	33.3 °C
Sp2	34.0 °C
Sp3	34.6 °C
Sp4	35.3 °C
Sp5	34.9 °C
Sp6	50.1 °C
Sp7	59.5 °C
Sp8	53.0 °C
Sp9	51.9 °C
Sp10	38.8 °C

Parameters	
Emissivity	0.95
Refl. temp.	20 °C

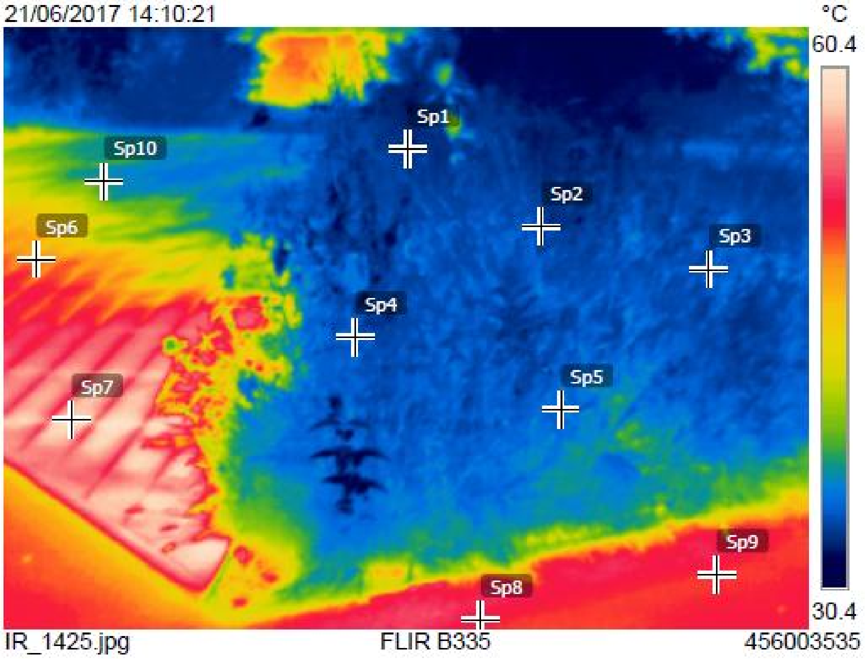


Figure 81. Photo and infrared image of Austrian gravel lawn at Queen Caroline Estate and surrounding grey infrastructure on the 21st June 2017. FLIR tools software was used to identify temperatures at selected points within the field of view. The hottest temperatures (>50 °C) were associated with the surrounding hard surfaces. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (34.1 °C). Temperatures observed in the vegetated gravel lawn were lower by almost 15 degrees with all temperatures around 35°C. The coolest areas were observed in the well-established vegetation (sp 1 at 33.3°C).

Measurements	
Sp1	34.6 °C
Sp2	34.4 °C
Sp3	35.8 °C
Sp4	34.8 °C
Sp5	37.7 °C
Sp6	42.5 °C
Sp7	41.9 °C
Sp8	37.6 °C
Sp9	36.1 °C
Sp10	40.1 °C

Parameters	
Emissivity	0.95
Refl. temp.	20 °C

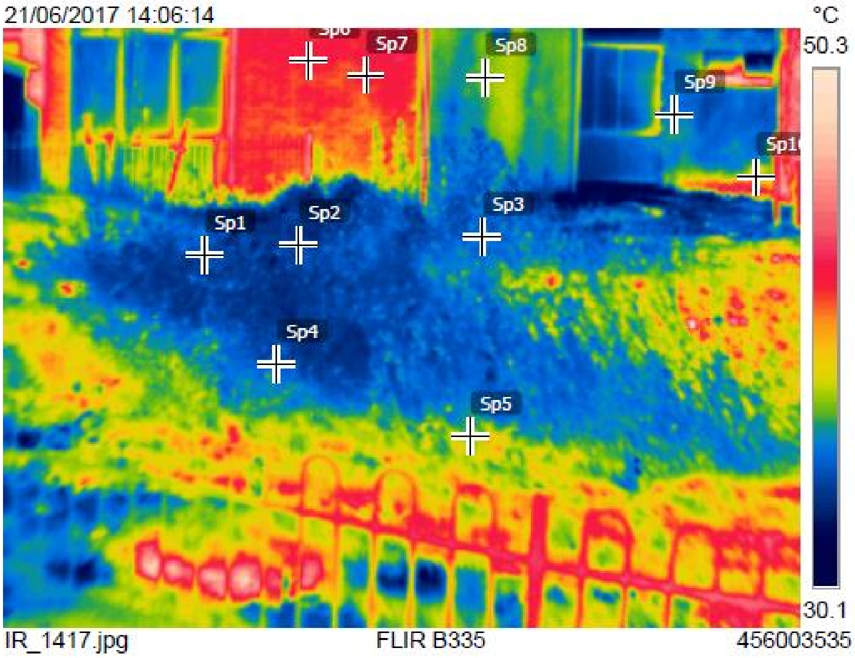


Figure 82. Photo and infrared image of a well-established detention basin at Queen Caroline Estate and surrounding grey infrastructure on the 21st June 2017. FLIR tools software was used to identify temperatures at selected points within the field of view. The hottest temperatures were associated with the surrounding walls and hard surfaces. All areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (34.1 °C). However temperatures observed in the vegetated areas were cooler with all temperatures around 37°C or less. The coolest areas were observed in the well-established vegetation (sp 2 at 34.4°C).

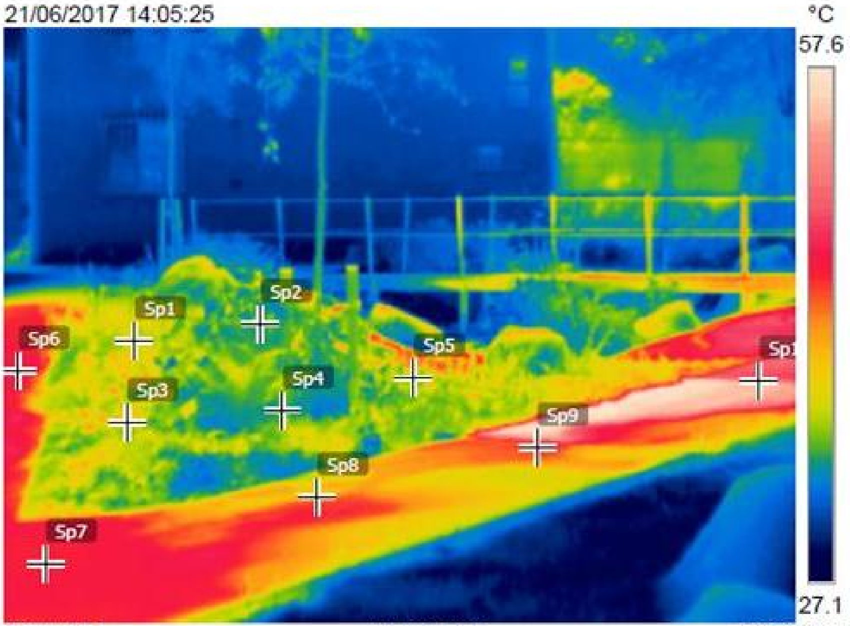
Measurements

Sp1	39.0 °C
Sp2	35.2 °C
Sp3	37.6 °C
Sp4	35.5 °C
Sp5	37.5 °C
Sp6	47.2 °C
Sp7	46.1 °C
Sp8	42.1 °C
Sp9	45.4 °C
Sp10	51.8 °C

Parameters

Emissivity	0.95
Refl. temp.	20 °C

21/06/2017 14:05:25



IR_1415.jpg FLIR B335 456003535

21/06/2017 14:05:25

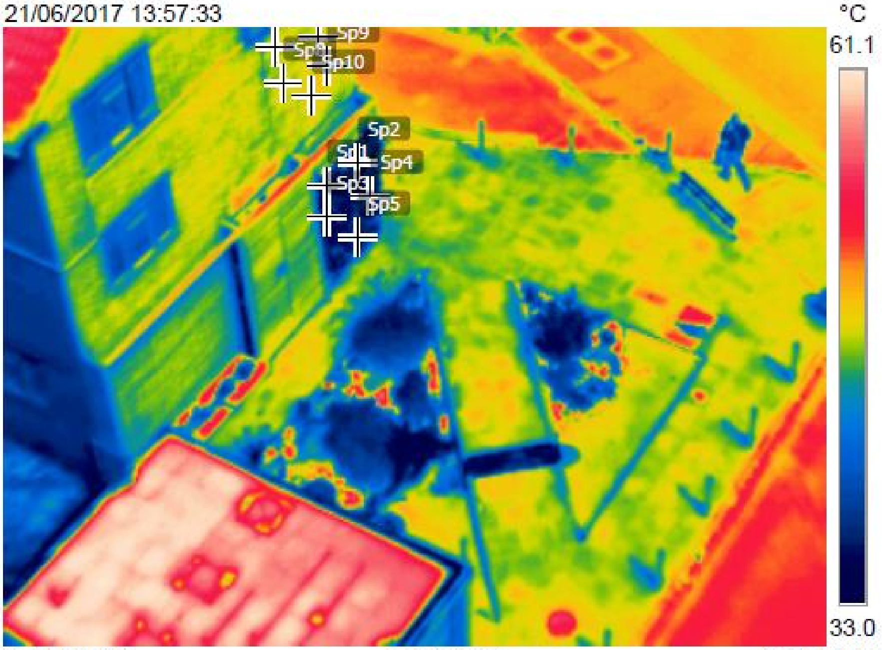
DC_1416.jpg

Figure 83. Photo and infrared image of the combined vegetated and permeable gravel rain garden at Queen Caroline Estate and surrounding grey infrastructure on the 21st June 2017. FLIR tools software was used to identify temperatures at selected points within the field of view. The hottest temperatures (>40 °C) were associated with the surrounding hard surfaces. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (34.1 °C). Temperatures observed in the vegetated area vary, but in general were lower with all temperatures <38°C. The coolest areas were observed in the well-established vegetation (sp 2 at 35.2°C).

Measurements	
Sp1	37.7 °C
Sp2	34.9 °C
Sp3	34.9 °C
Sp4	36.0 °C
Sp5	35.4 °C
Sp6	47.7 °C
Sp7	48.5 °C
Sp8	48.3 °C
Sp9	49.5 °C
Sp10	49.0 °C

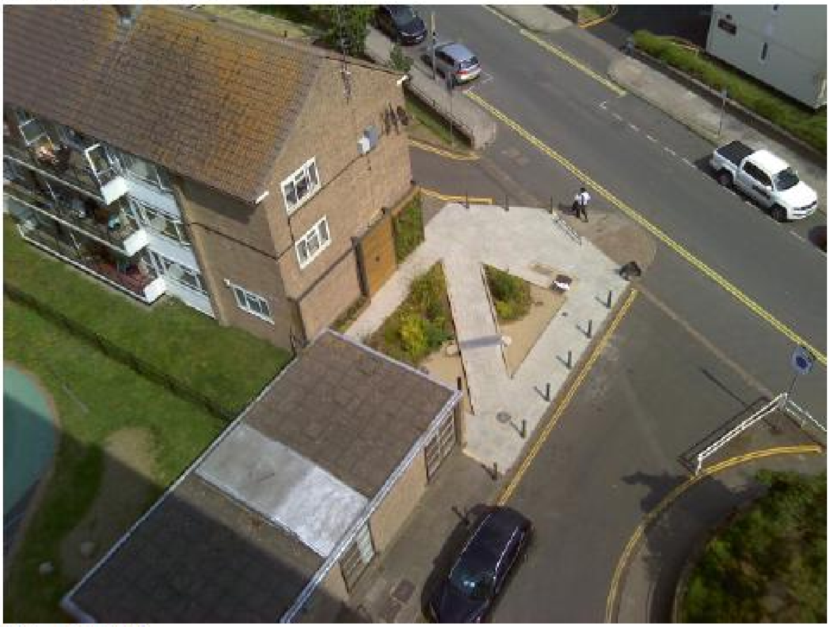
Parameters	
Emissivity	0.95
Refl. temp.	20 °C

21/06/2017 13:57:33



IR_1405.jpg FLIR B335 456003535

21/06/2017 13:57:33



DC_1406.jpg

Figure 84. Photo and infrared image of the vertical rain garden at Queen Caroline Estate and surrounding grey infrastructure on the 21st June 2017. FLIR tools software was used to identify temperatures at selected points within the field of view. The hottest temperatures (>45 °C) were associated with the surrounding hard surfaces (including walls, roads and paving). These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (34.1 °C). Temperatures observed in the newly installed vertical rain garden were lower with all temperatures <38°C. The coolest areas were observed in the planted green wall area (sp 3 at 34.9°C).

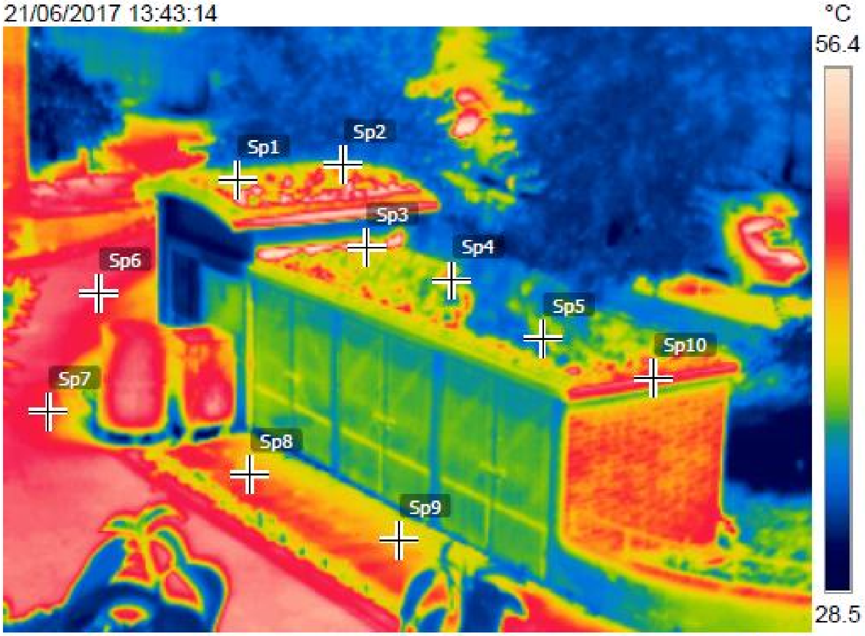
Measurements

Sp1	41.4 °C
Sp2	41.6 °C
Sp3	42.0 °C
Sp4	41.1 °C
Sp5	37.6 °C
Sp6	49.6 °C
Sp7	47.5 °C
Sp8	45.5 °C
Sp9	43.9 °C
Sp10	50.6 °C

Parameters

Emissivity	0.95
Refl. temp.	20 °C

21/06/2017 13:43:14



IR_1371.jpg FLIR B335 456003535

21/06/2017 13:43:14

DC_1372.jpg

Figure 85. Photo and infrared image of one of the pram shed green roofs at Queen Caroline Estate (Alexandra house) and surrounding grey infrastructure on the 21st June 2017. FLIR tools software was used to identify temperatures at selected points within the field of view. The hottest temperatures (>45 °C) were associated with the surrounding hard surfaces (including walls, roads and paving). These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (34.1 °C). Temperatures observed in the newly installed vertical rain garden were lower with all temperatures <42°C. The coolest areas observed were on the green wall (sp 5 at 37.6°C).

Richard Knight House Experimental plots 21st June 2017

Thermal images were also taken of each of the experimental plots on the Richard Knight House green roof. This was carried out to assess whether there were consistent differences in the thermal performance in relation to the experimental design of each plot. Results for the 21st June are presented in Table 23 along with values for the standard flat roof on the neighbouring building.

Table 23. Average temperatures recorded on the green roof experimental plots of Richard Knight House and neighbouring standard flat roof, 21st June 2017. Temperatures calculated using a FLIR B335 thermal imaging camera. Images were analysed using FLIR Tools software. Ten spots were placed on the image of each green roof test plot and the standard roof using stratified randomisation. An average of the temperatures within each of these test plots was calculated.

	Experimental design of area			Observation	
Experimental area	Substrate depth	Planting type	Aquaten layer?	Average temperature	S.E.
1	100	plug	no	43.18	1.35
2	50	plug	no	33.51	1.47
3	130	plug	no	34.02	0.84
4	100	seed	no	36	1.17
5	50	seed	no	44.65	1.73
6	130	seed	no	42.01	1.35
7	100	seed	yes	36.36	1.61
8	50	seed	yes	45.66	0.99
9	130	seed	yes	33.99	1.2
10	100	plug	yes	34.78	0.84
11	50	plug	yes	39.72	1.15
12	130	plug	yes	38.1	1.62
Control roof	N/A	N/A	N/A	55.74	0.99

A Kruskal-Wallace non-parametric test was carried out on the data to assess whether there was a significant difference between the temperatures recorded across the test plots. Non-parametric testing was used due to the low sample number (n=10). For the thermal imaging date (the 21st June 2017) a significant difference was found between the test plots ($p<0.001$).

Following the positive results for significance obtained by the Kruskal-Wallace test, Mann-Whitney U exact tests were performed to identify where significant thermal differences were recorded.

Selected Mann-Whitney results from the thermal images taken on the 21st June 2017 are presented in Table 24:

Table 24. Mann-Whitney test results for temperatures recorded on the green roof experimental plots of Richard Knight House and neighbouring standard flat roof, 21st June 2017. Temperatures calculated using a FLIR B335 thermal imaging camera. Images were analysed using FLIR Tools software. Ten spots were placed on the image of each green roof test plot and the standard roof using stratified randomisation. Values were compared for statistically significant difference at a $p < 0.05$ significance level.

Test	Significance test	Warmest roof experiment	Significant difference?
Green roof vs control	$p < 0.001$	control	sig
Aquaten vs no Aquaten	0.543	N/A	n/s
Aquaten plug vs Aqauten seed	0.539	N/A	n/s
No aquaten plug vs no aquaten seed	0.01	non aquaten seeded	sig
50mm substrate vs 100mm	0.021	50mm	sig
50mm vs 130mm	0.009	50mm	sig
100mm vs 130mm	0.637	N/A	n/s

It must be noted that, because samples were taken from single plots, pseureplication may have contributed to statistical results. However, analysis had to be carried out within the limits of the experimental design which included no replication.

Similarly to the previous monitoring periods (Connop & Clough 2016; Connop *et al*. 2016), a key observation from this period of study was that even on a typical summer's day the green roof plots were significantly cooler than those on the neighbouring – non green - control roofs. The experimental green roof continued to demonstrate the beneficial cooling effect that green roofs can have in high density urban areas. This evidence supports the theory that green roofs can contribute to reducing the urban heat island effect and associated thermal stress.

Results from the 2017 survey of the experimental green plots show fewer significant relationships than previous monitoring periods on this green roof: In the summer 2017, there was no recorded significant difference in observed temperatures between the Aquaten and non-Aquaten roofs. Similarly to the previous monitoring periods (Connop & Clough 2016; Connop *et al*. 2016), there was no significant difference between the seeded Aquaten plots and those that were plug planted. It is possible that the significantly reduced temperatures previously recorded on Aquaten plots compared to non-Aquaten was limited in effect to the establishment phase of the roof. This year's survey indicated that this impact had reduced to the point where no significant difference was observed, now that the vegetation was more established across all roof plots.

The results corresponded with the previous monitoring periods in relation to patterns associated with substrate depth. The 2017 survey provided additional evidence that the shallowest substrate plots (50mm depth) were significantly warmer than those plots with 100 mm or 130 mm substrate. This may also have been due to poorer establishment of vegetation on the shallower plots, as detailed during the vegetation surveys on the roof (Section 3.6). Due to the non-randomised nature of the plots, however, it is impossible to rule out the possibility that the plots in the centre of the roof (the 50 mm plots) were hotter due a cooling at the roof edges on the other plots. No significant difference was recorded between the 100 mm and 130 mm plots.

On the non-Aquaten side of the roof, the seeded plots were the warmest plots compared to the plug planted plots. This result contrasted with previous monitoring periods, when plug planted plots were recorded as warmer. This may have been the result of more comprehensive vegetation cover on the plug planted plots than the seeded plots on the area of the roof without Aquaten in June 2017. This theory was supported by the greater floral diversity recorded on plug planted plots, but not in terms of proportion of bare ground (Section 3.6). In contrast, on the Aquaten side of the roof no significant difference in temperature was found between the plug planted and seeded plots. No further analysis of data was carried out due to the difficulty in interpreting the results related to the non-randomised nature of the plot layout.

Mary House Vertical Rain Garden - thermal monitoring

As an addition to the contracted monitoring programme, the SRI hosted a summer intern as part of UEL's undergraduate research intern programme. The Intern Rayhan Amal (an engineering undergraduate student) was trained in the use of the thermal camera and a thermohygrometer. This equipment was then used to investigate the thermal properties of the newly vertical rain garden that was installed at Queen Caroline Estate during the spring of 2017 (Figure 86) . The vertical rain garden was installed onto the side of Mary House (Figure 87) and was designed as a SuDS feature that intercepted and stored rainwater from a downpipe of Mary House (Figure 88). In addition to providing a SuDS function, the vertical rain garden was also designed to provide habitat for pollinators, aesthetic benefits for local residents and provide a thermal cooling service.

The aim of the internship study, was to identify whether the green wall resulted in a cooling effect in comparison to neighbouring control walls. The study was also designed to investigate the distance of any such such cooling effect away from the vertical green wall.

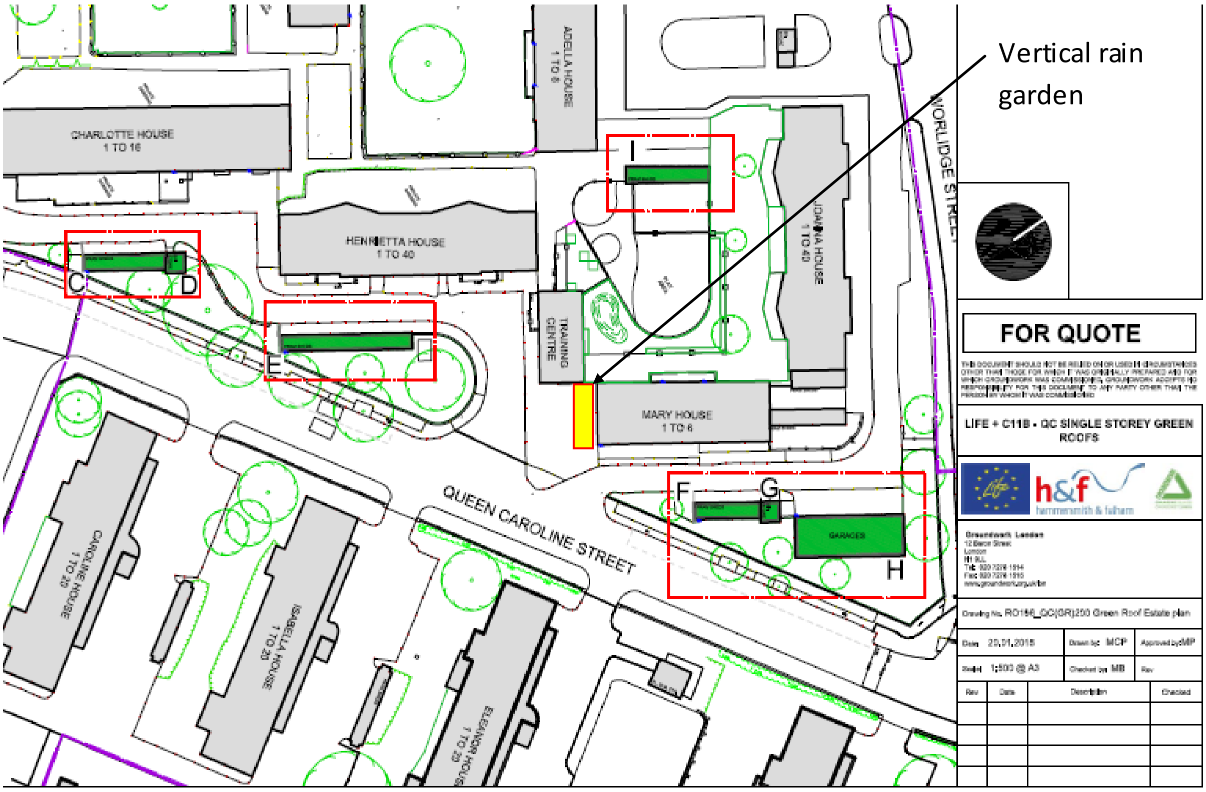


Figure 86. Plan showing location of the vertical rain garden on Mary House, Queen Caroline Estate, 2017. Location of vertical rain garden is shown as a yellow rectangle.

Figure 87. Vertical rain garden installed and in bloom on Mary House, Queen Caroline Estate, 2017. The vertical rain garden comprised a green wall, stormwater storage tank and green facade.

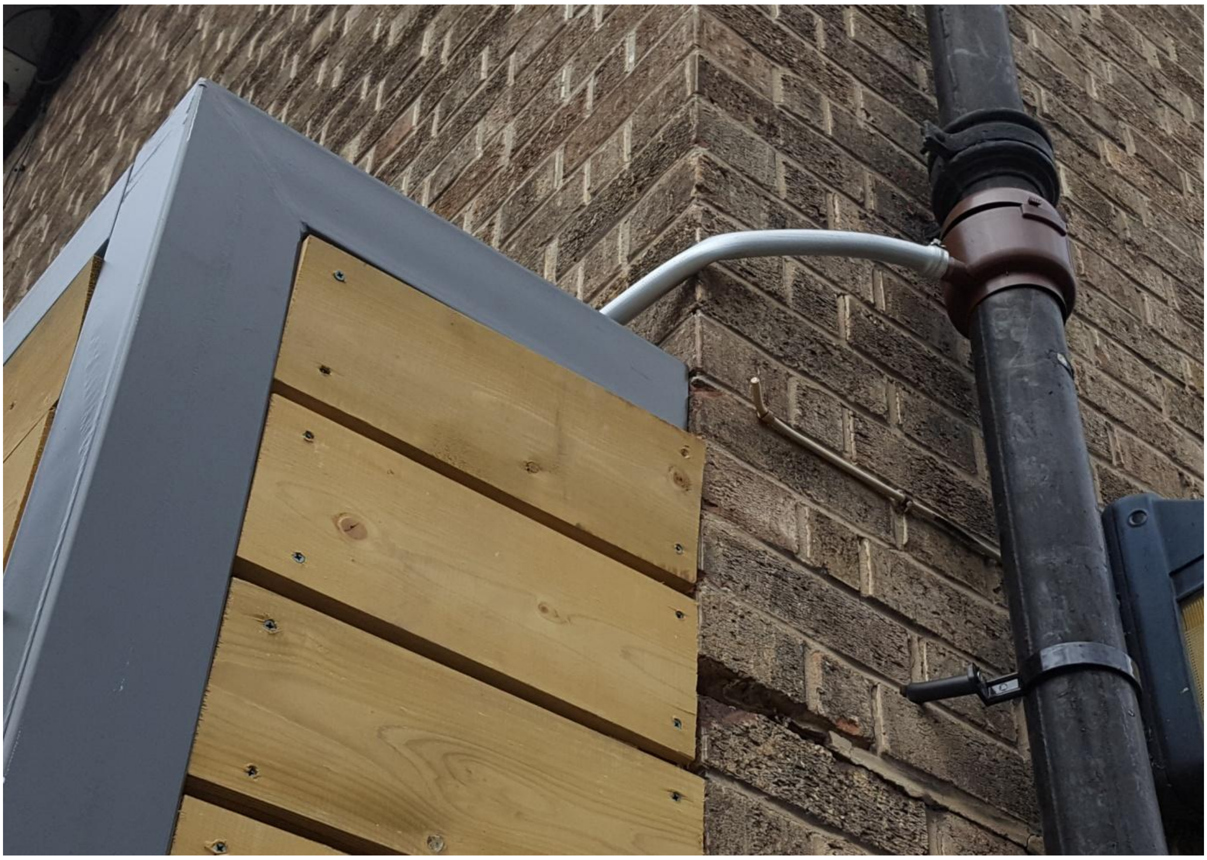


Figure 88. Stormwater interception mechanism that takes rainwater from the downpipe of Mary House and fills the vertical rain garden storage tank, Queen Caroline Estate, 2017. The vertical rain garden comprised a green wall, stormwater storage tank and green facade.

Methodology

In order to generate accurate data on a control wall, the thermal profiles of three walls were measured using a thermal camera prior to the vertical rain garden installation . All three walls had the same aspect, shading and brickwork as the Mary House wall. On one of the walls the vertical rain garden was constructed. The other two walls remained the same throughout the study. These two walls were used as the control walls for comparative performance.

Thermal pictures were taken of all walls from a distance of roughly 10 m and then from an elevated position, looking down at the walls and surrounding surfaces. 15 temperature hotspots were calculated for each thermal image using Flir QuickReport. An average temperature was calculated for each wall to compare the temperature difference between the wall on which the green wall was to be installed and the control walls.

Following installation of the vertical rain garden, an Extech HT30 Thermohygrometer with Heat Stress Index' was used to measure temperature, relative humidity[a] and heat stress index[b] for each of the walls. The thermohygrometer was attached to a tripod to maintain a consistent height of measurement (1.3 m - approximately an average chest height) . Measurements were taken from a mid-point of each wall right next to the wall. The tripod was then moved to take reading at 10cm intervals away from the walls; up to a maximum of 100 cm away from the wall.

Potential confounding factors

There are several potential confounding factors that could influence the results of this assessment and should be considered when interpreting the results:

- a rain garden had been installed in relatively close proximity to the vertical rain garden, and this may also have contributed to any cooling/humidity effect.
- due to the nature of the recording equipment, simultaneous monitoring could not be carried out, thus measurements had to be taken at walls consecutively. Attempts were made to minimise the time difference between measurements at each wall, but this could also have influenced results.

Thermal Images

A set of thermal images were taken using the 'thermal FLIR camera', of the green wall panel and the two control walls.

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[a] *Relative humidity (RH): Relative humidity is the ratio of the water vapour present in the air relative to the amount that would be present if the air was saturated. It is given as a percentage.*

[b] *Heat Stress Index (HIS): The heat stress index is the measurement of how hot it actually feels. It is a combination of humidity, temperature and air movement.*

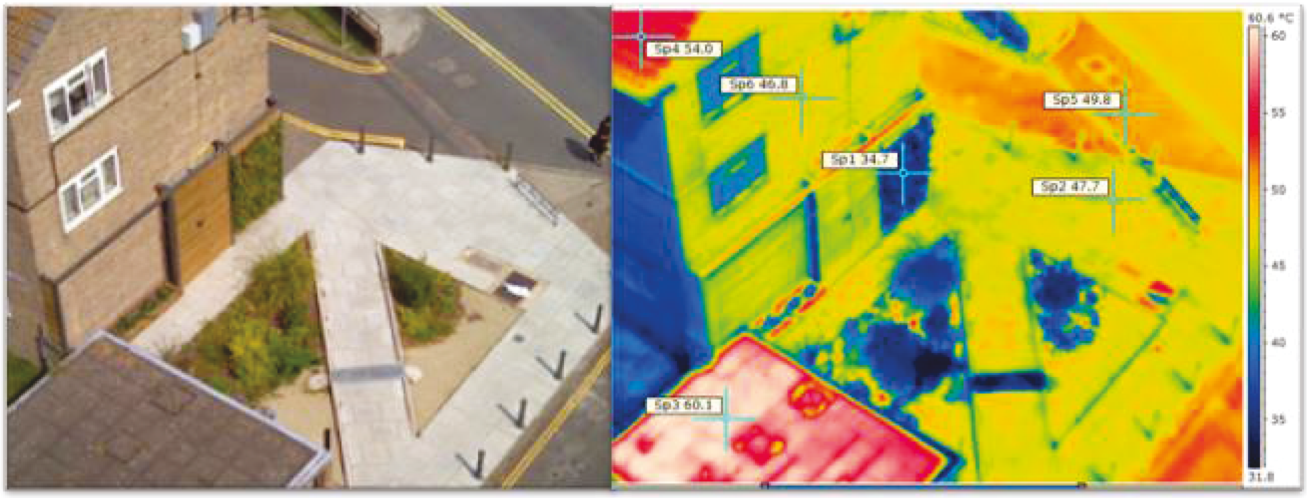


Figure 89. Elevated photo and thermal camera image of the vertical rain garden on Mary House, Queen Caroline Estate.

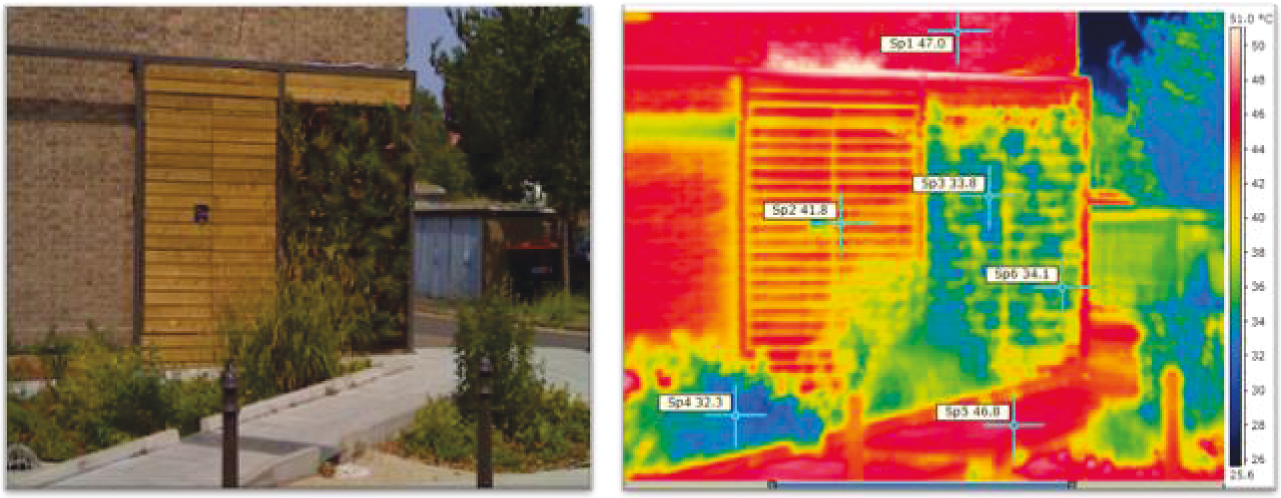


Figure 90. Ground level photo and thermal camera image of the vertical rain garden on Mary House, Queen Caroline Estate.

Figures 89 and 90 demonstrate that the areas covered in vegetation were cooler when compared to their surroundings. The temperature of the vegetation areas ranged from 33°C to 35°C. Surrounding surfaces were typically more than 10°C warmer. Unvegetated roof area temperatures ranged from 54°C to 60°C. Roads, walls and other surfaces ranged from 41°C to 49°C. This reduced temperate on the vegetated area was presumably due to a combination of evapotranspiration by plants extracting heat from the air and the ability of the plants to intercept solar radiation, reducing absorption and reflectance by the brickwork of the building. Both of these factors would contribute to lowering surface and air temperature.

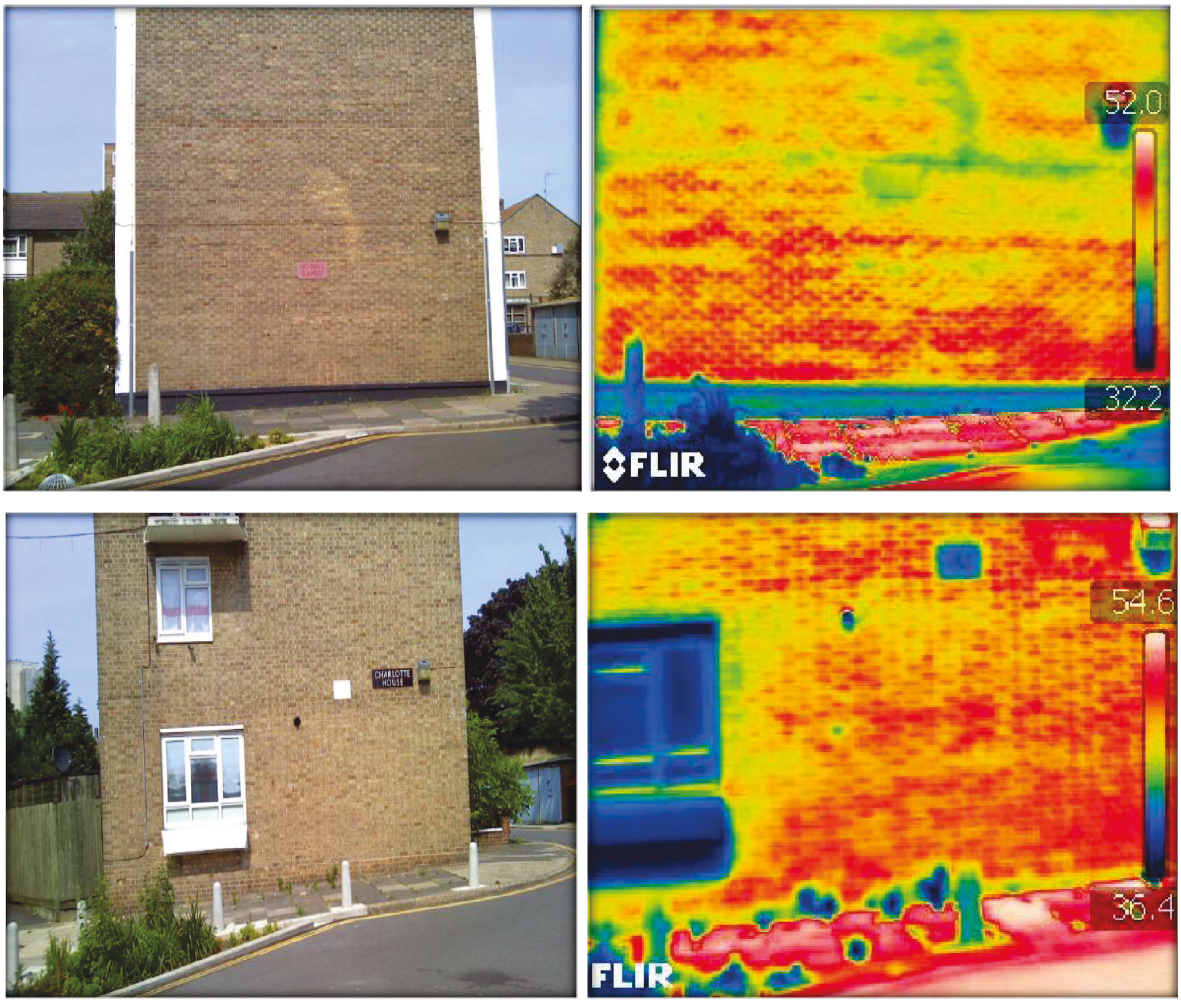


Figure 91. Photos and thermal images of control walls neighbouring the vertical rain garden, Queen Caroline Estate. The walls were used as controls as they had similar aspect, shading and brickwork to the wall on which the vertical rain garden was installed.

It can be seen that both control walls were recording high temperatures ranging from 40°C to 50°C when exposed to the direct sunshine. The pavement and road temperatures were also hot with temperatures as high as 54°C. This was due to the surfaces being made of materials that absorbed and radiated heat from the sun.

Results of thermal image analysis

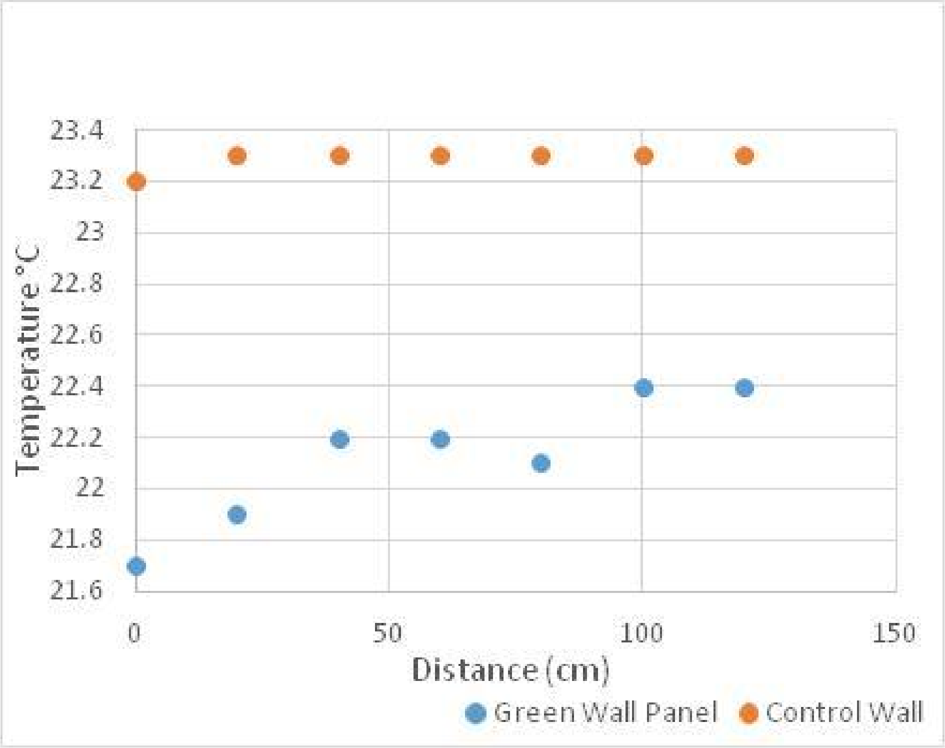
Table 25 contains the temperature recorded at 15 random points on each of the walls taken from the thermal camera. The images were taken on the 21st June 2017. An average temperature was calculated from these points for each of the walls and the temperature difference compared to the vegetated wall was also calculated.

Table 25. Hotspot temperatures, average temperatures and temperature differences between the vertical rain garden and comparative control brick walls at Queen Caroline Estate, Hammersmith. Images were taken on the 21st June 2017.

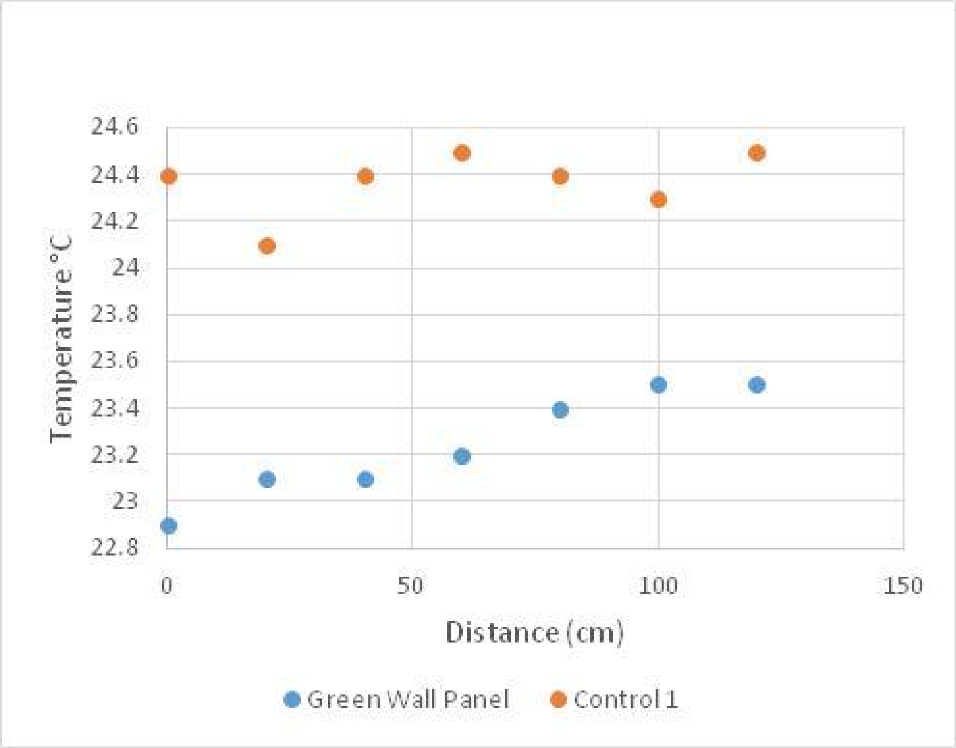
Thermal hotspot	Control wall 1 (°C)	Control wall 2 (°C)	Green wall 1 (°C)	Green wall 2 (°C)
1	45.6	47.7	36.5	38
2	46.7	46.9	34.2	37.4
3	45.8	46.6	34.4	35.8
4	47.3	47.9	36.1	37.1
5	45.7	48.3	33.4	36
6	46.4	48	34.2	39.5
7	46.8	47.6	34.1	36.4
8	46.5	48.4	36.5	37
9	44.8	48.6	35.2	34.8
10	45.3	47.8	35.1	35
11	46.5	48.4	34.8	35.3
12	46.4	47.2	34.3	34.5
13	45.7	48.4	35.7	37.3
14	45.1	48.2	34.4	36.7
15	45.9	47.7	34.7	37.6
AVG (°C)	46.0	47.8	34.9	36.6
AVG (°C)	46.9		35.7	
Δ Temp (°C)	11.2			

Results of thermal monitoring

Figure 92 contains the results from thermohygrometer monitoring of the vertical rain garden and the control wall.



i)



ii)

Figure 92. i) Minimum and ii) maximum temperatures readings taken at 10 cm intervals away from the vertical rain garden and control wall, Queen Caroline Estate, Hammersmith. Readings were taken using a thermohygrometer fixed to the top of a tripod. The vertical rain garden was vegetated, the control wall was brickwork.

Summary

Whilst the experimental design and replication was limited and there were some potentially confounding factors, the monitoring provided some evidence that the vertical rain garden was providing mitigation for the heat island effect in this high-density urban area. The study also provided evidence that this effect declined steadily with distance away from the wall. This was presumably due, in large part, to the scale of the vertical rain garden in comparison with surrounding hard surfaces. Whilst the surveys were not carried out on one of the hottest days of the year, results from the thermohygrometer survey demonstrated that these effects were apparent even on a typical summer day.

In contrast, the thermal images were taken on a particular hot day. Analysis of these images identified that the vertical rain garden surface was approximately 11°C cooler than the neighbouring control walls. This was a particularly encouraging result in light of the fact that the vegetation on the vertical rain garden was not fully developed at the time of the survey.

The combination of these results demonstrated that the vertical rain garden could have had a beneficial effect for residents in terms of providing a thermal comfort zone, in addition to the other ecosystem service benefits that it provided. Further survey would be required to quantify the scale of this effect. Recommendations for such further work include:

- Using multiple thermohygrometers to capture simultaneous data, or installing dataloggers for continuous data capture.
- Taking measurements at further distances away from the wall.
- Comparing the performance of vertical rain gardens with those for other types of green wall systems.

3.6 Biodiversity monitoring

Comparative botanical surveys were carried out at Richard Knight House on 14th June, 11th August and the 14th September 2017. A quadrat sampling methodology was used to monitor plant performance and followed the same protocol used in the previous year (Connop and Clough 2016). A 50 cm x 50 cm quadrat was placed at three locations within each of the green roof experimental plots using a systematic sampling approach. The quadrat used was divided into a grid of 100 sub-units; the presence of each higher plant species present within the quadrat was recorded (species richness), and then a count was made of the number of grid sub-units in which the species was present (i.e. a species present in all sub-units within the quadrat would score a total abundance of 100). Where possible, all plants were identified to species level. Additionally, for each quadrat a count sub-units containing new shoots (i.e. new plant growth that was as yet unidentifiable to genus or species) and bare ground was also recorded.

A full list of plant species recorded during the botanical surveys in 2017 is show in Table 26. A total of 57 plant species were recorded in quadrats during the three surveys.

Table 26. Full list of plant species recorded during botanical surveys on the Richard Knight House green roof in 2017.

Species	**Common name**
Achillea millefolium	Yarrow
Agrostis stolonifera	Creeping bentgrass
Allium schoenoprasum	Chives
Anthemis tinctoria	Corn chamomile
Anthyllis vulneraria	Kidney vetch
Armeria maritima	Thrift
Calamintha ascendens	Common calamint
Capsella bursa-pastoris	Shepherd's purse
Centaurea cyanus	Cornflower
Clinopodium vulgare	Wild basil
Conyza sumatrensis	Guernsey fleabane
Daucus carota	Wild carrot
Dianthus carthusianorum	Carthusian pink
Dianthus deltoides	Maiden pink
Festuca glauca	Blue fescue
Festuca rubra	Red fescue
Galium mollugo	Hedge bedstraw
Galium palustre	Common marsh bedstraw

Species	**Common name**
Galium verum	Lady's bedstraw
Geranium molle	Dove's-foot Crane's-bill
Helianthemum nummularium	Common rock-rose
Hypericum perforatum	Perforate St John's-wort
Leucanthemum vulgare	Oxeye daisy
Linaria vulgaris	Common toadflax
Lotus corniculatus	Birdsfoot trefoil
Lychnis flos-cuculi	Ragged-robin
Malva moschata	Musk mallow
Medicago lupulina	Black medick
Melilotus officinalis	Ribbed melilot
Origanum vulgare	Oregano
Petrorhagia saxifraga	Tunic flower
Helminthotheca echioides	Bristly oxtongue
Pilosella aurantiaca	Fox-and-cubs
Pilosella officinarum	Mouse-ear hawkweed
Plantago lanceolata	Ribwort plantain
Polypogon viridis	Water bent
Poterium sanguisorba	Salad burnet
Prunella vulgaris	Selfheal
Sagina procumbens	Procumbent pearlwort
Salvia pratensis	Meadow clary
Scabiosa columbaria	Small scabious
Scorzoneroides autumnalis	Autumn hawkbit
Sedum acre	Biting stonecrop
Sedum album	White stonecrop
Sedum forsterianum	Rock stonecrop
Sedum oreganum	Oregon stonecrop
Sedum rupestre	Reflexed stonecrop
Sedum sexangulare	Six-sided stonecrop
Sedum spurium	Two-row stonecrop
Silene dioica	Red campion
Sonchus oleraceus	Smooth sow-thistle
Stellaria media	Chickweed
Thymus pulegioides	Large thyme
Trifolium dubium	Lesser trefoil
Trifolium pratense	Red clover
Trifolium repens	White clover
Veronica chaemadrys	Germander speedwell

The diversity of flower types (i.e. composite, tubular, umbel), and flowering season/duration of the plant species recorded on the roof should provide a valuable resource for wildlife, including pollinator groups. The species recorded in 2017 included those that were plug planted, seeded and species that had colonised the roof naturally.

14th June 2017 survey

By the third year of conducting botanical surveys, vegetation on the Richard Knight House green roof experimental plots was becoming well established. Analysis of the pattern of distribution in relation to the plot treatments that was undertaken in 2016 is repeated for 2017. Due to the lack of randomised replication of individual experimental treatments and potential confounding factors in the experimental design, it was not possible to draw detailed conclusions regarding their influence on plant development. Moreover, such experimental design limitation mean that repeated sampling within plots was necessary which can lead to issues of pseudoreplication in statistical analysis. Nevertheless, it was possible to identify certain trends from the data that indicate areas for more detailed study.

Floral species richness

Overall, forty-five floral species were recorded in the thirty-six 50 x 50 cm quadrats. Of these, four were grass species and the remainder were wildflowers. Average floral species richness was higher in quadrats in plug planted plots than seeded plots (Figure 93), but a Mann-Whitney U Exact two-tailed test demonstrated that there was no significant difference between the two vegetation treatments (p = 0.213).

In both Aquaten and non-Aquaten areas of the roof, average species richness was higher for plug planted species compared to seeded species, but Mann-Whitney U Exact two-tailed tests confirmed these differences were not significant (Aquaten areas p = 0.143: non-Aquaten areas: p = 0.719). When vegetation treatments were analysed individually, seeded species richness was lower in quadrats in Aquaten areas compared to non-Aquaten areas, but the difference was not significant (p = 0.109). Plug planted species richness also showed no significant difference in relation to the presence/absence of Aquaten (p = 0.929).

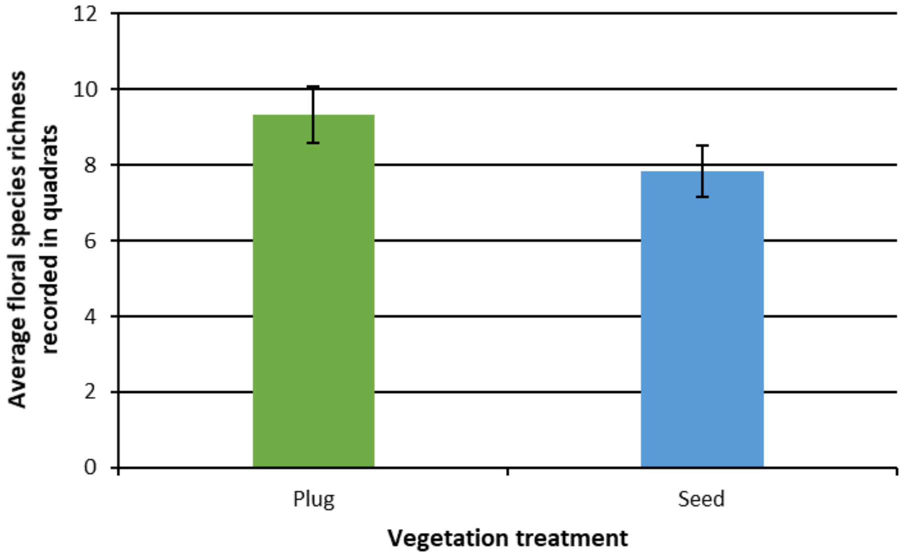


Figure 93. Average floral species richness on the Richard Knight House green roof, 16th June 2017. Averages are calculated on the number of floral species recorded in 18 quadrats for the two vegetation treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

Vegetation cover

In terms of colonisation of the plots and vegetation cover, the number of quadrat sub-units containing bare ground was used as a proxy for vegetation cover. In June, the average amount of bare ground recorded in the plug planted and seeded plots was similar (Figure 94), and a Mann-Whitney U Exact two-tailed test confirmed that the difference between treatments was not significant (p = 0.213).

For both vegetation treatments, mean vegetation cover was greater in Aquaten areas compared to non-Aquaten areas of the roof, but this difference not significant difference (seeded plots on Aquaten and non-Aquaten areas of the roof: p = 1.000; plug planted Aquaten and non-Aquaten areas: p = 0.565).

Vegetation cover was greatest in plots with the deepest substrate treatment (130 mm), however a Kruskal-Wallis non-parametric test demonstrated this difference was not significant (p = 0.114).

Kruskal-Wallis non-parametric tests of vegetation cover at different substrate depths on the Aquaten and non-Aquaten areas revealed there was no significant difference within non-Aquaten plots, but there was a significant difference between substrate depths in Aquaten plots (p = 0.005). Vegetation cover was highest in 130 mm plots in Aquaten areas (Figure 95), and post-hoc Mann-Whitney U Exact two-tailed tests confirmed that the difference was significant (130 mm versus 50 mm: $p = 0.006$; 130 mm versus 100 mm: $p = 0.008$). There was no significant difference between 50 mm and 100 mm plots with Aquaten ($p = 0.623$). This finding indicated that using Aquaten in combination with greater substrate depths on a green roof could enhance vegetation growth and cover.

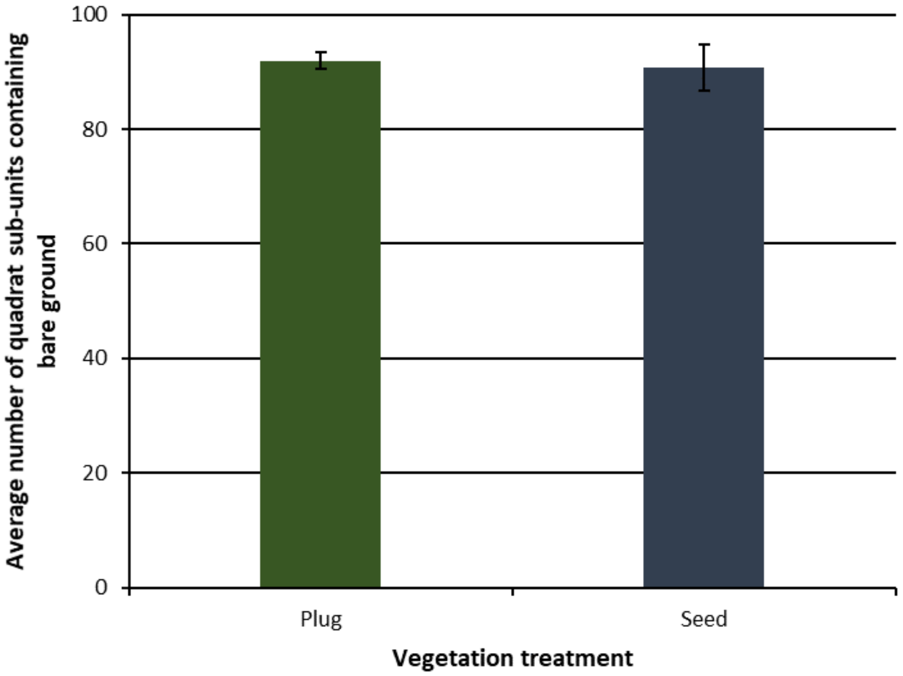


Figure 94. Average number of quadrat sub-units containing areas of bare ground on the Richard Knight House green roof, 16th June 2017. A lower proportion of bare ground equates to greater vegetation cover. Averages are calculated on the number of sub-units out of 100 sub-units within which bare ground was recorded for 18 quadrats for the two vegetation treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

A Kruskal-Wallis non-parametric test was carried out to compare vegetation cover on each test treatment and assess whether there was a significant difference. Non-parametric testing was used due to the low sample number (n=3). The test revealed that there was a significant difference between test plots when compared individually ($p = 0.05$). On average, the greatest vegetation cover was recorded on an Aquaten plot with the deepest substrate treatment (130 mm) which was seeded. Closer inspection of the data revealed that vegetation cover in this particular experimental plot was predominantly characterised by a single grass species *Festuca rubra*. The implications of dominant grass cover on green roofs is discussed further below.

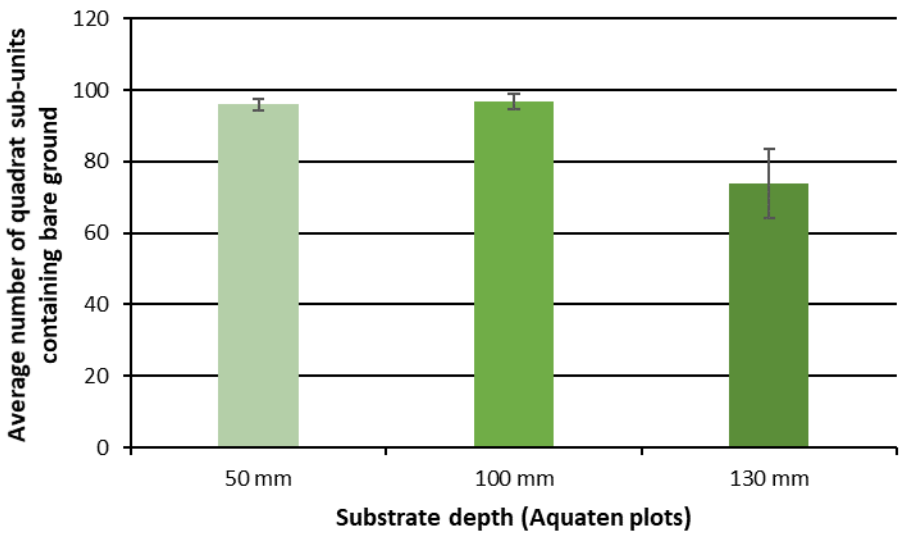


Figure 95. Average number of quadrat sub-units containing areas of bare ground on Aquaten plots at each substrate depth, Richard Knight House green roof, 16th June 2017. A lower proportion of bare ground equates to greater vegetation cover. Averages are calculated on the number of sub-units out of 100 sub-units within which bare ground was recorded for 6 quadrats in Aquaten plots at the substrate depths 50 mm, 100 mm, and 130 mm. Error bars represent standard error of the mean.

Grass cover

In addition to vegetation cover, grass cover within quadrats was also analysed. Some grass cover is considered to be desirable for green roofs. Grasses can offer a resource for biodiversity, and in terms of providing cover and urban cooling benefits, some grass is a positive feature. However, on biodiverse roofs a key target is the provision of floral resources for pollinators, therefore dominant grass swards are considered undesirable. Moreover, grasses are typically less resilient to drought-stress than wildflowers, therefore green roofs dominated by grasses would be expected to provide less urban cooling benefits during prolonged hot periods than a corresponding cover of wildflowers. To assess the grass cover development on different green roof treatments on Richard Knight House, the number of quadrat sub-units in which grasses were counted was compared.

Results revealed that substantially more grass was recorded on the seeded plots than on the plug planted plots (Figure 96), and a Mann-Whitney U Exact two-tailed test confirmed that this difference between treatments was significant ($p < 0.001$). As was recorded in the first survey in 2016, grass was the dominant vegetation cover for a number of the seeded plots, however the mean cover was much lower than in 2016 when it was close to 100%.

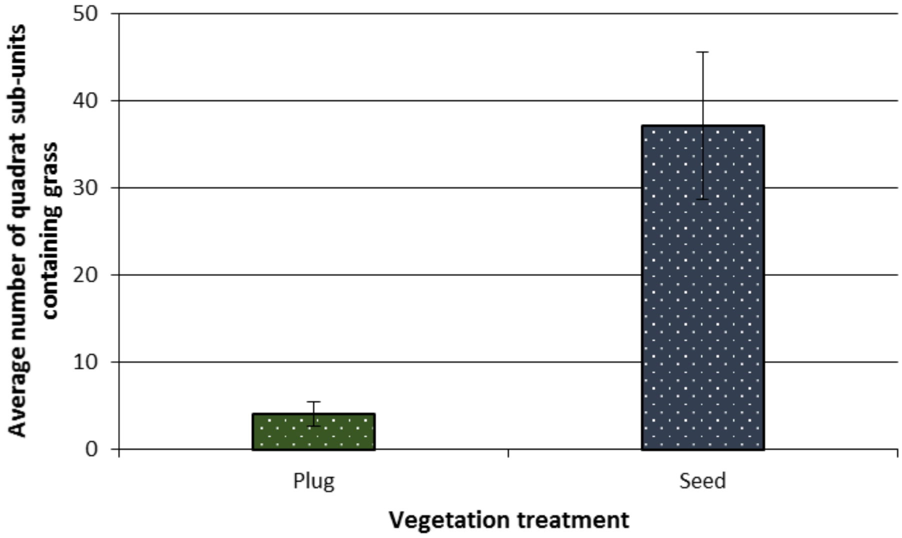


Figure 96. Average number of quadrat sub-units containing grass on the Richard Knight House green roof, 16th June 2017. Averages are calculated on the total number of records of all grass species within each quadrat within each experimental plot for 18 quadrats for the two vegetation treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

11th August 2017 survey

In contrast to the drought-stressed vegetation conditions recorded in August 2016, the fairly unsettled weather experienced during the summer in 2017 meant that vegetation on Richard Knight House green roof was in a much healthier condition for the second visit of the 2017 survey season. This may also have been partly due to the more established vegetation in 2017 being more tolerant to drought.

Floral species richness

Floral species richness was higher than in the June survey with forty-seven species being recorded in the thirty-six 50 x 50 cm quadrats. Of these, three species were grass and the remaining species were wildflowers. In contrast to June, average floral species richness was slightly higher in seeded plots rather than plug planted plots (Figure 97). A Mann-Whitney U Exact two-tailed test confirmed there was no significant difference in species richness between the treatments (*p* = 0.472).

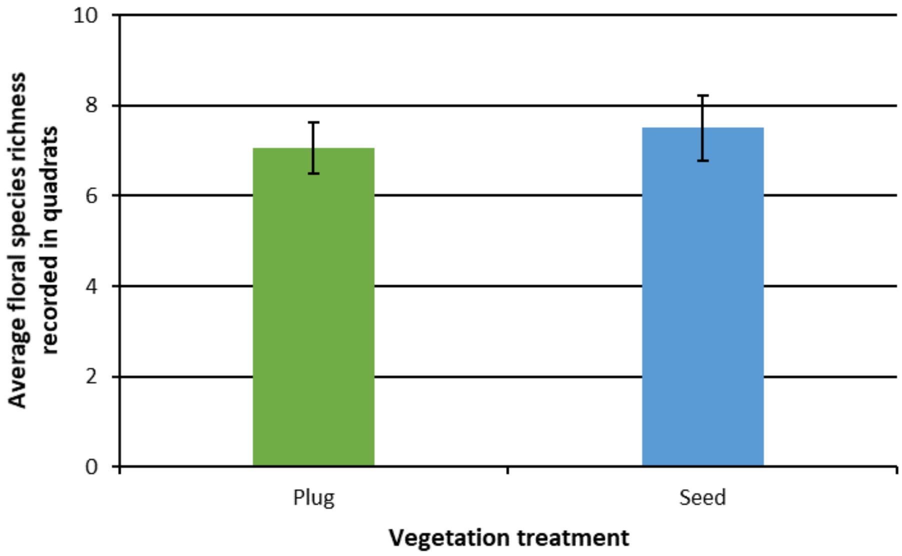


Figure 97. Average floral species richness on the Richard Knight House green roof, 11th August 2017. Averages are calculated on the number of floral species recorded in 18 quadrats for the two vegetation treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

During botanical surveys the previous year, sampling in August 2016 coincided with a period of prolonged drought, and plug planted plots had significantly greater species richness than seeded plots. The results for August 2017 demonstrated that this pattern is reversible when weather conditions are more favourable to green roof vegetation growth.

As was recorded in June, in both Aquaten and non-Aquaten areas of the roof average species richness was higher for plug planted species compared to seeded species, but Mann-Whitney U Exact two-tailed tests confirmed these differences were not significant (Aquaten *p* = 0.689: non-Aquaten areas: *p* = 0.719). However, when vegetation treatments were analysed individually, both seeded and plug planted vegetation species richness was now higher in non-Aquaten areas, although the difference was not significant (seeded Aquaten versus non-Aquaten areas: *p*= 0.592; plug planted Aquaten versus non-Aquaten areas: *p* = 0.325).

Vegetation cover

In terms of colonisation of the plots and vegetation cover, the number of quadrat sub-units containing bare ground was used as a proxy for vegetation cover. As with the June survey, the average amount of bare ground recorded in seeded and plug planted plots was similar (Figure 98), and a Mann-Whitney U Exact two-tailed test confirmed there was no significant difference (*p* = 0.255). On average vegetation cover had increased for both vegetation treatments since the June survey.

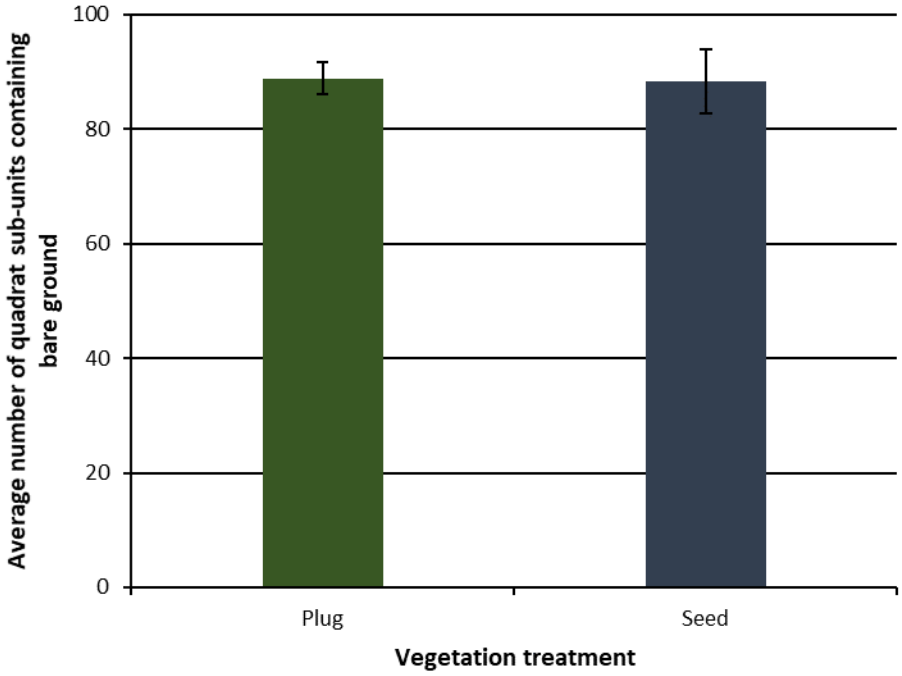


Figure 98. Average number of quadrat sub-units containing areas of bare ground on the Richard Knight House green roof, 11th August 2017. A lower proportion of bare ground equates to greater vegetation cover. Averages are calculated on the number of sub-units out of 100 sub-units within which bare ground was recorded for 18 quadrats for the two vegetation treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

There was no significant difference in seeded vegetation cover recorded within Aquaten and non-Aquaten areas of the roof (*p* = 0.657). However, for plug planted species, vegetation cover was now significantly greater on non-Aquaten plots compared to Aquaten areas (*p* = 0.012 and Figure 99). This was a change from the result in June when cover was slightly higher on Aquaten areas. Aquaten has been used on green roofs because its water retention properties may offer extended passive irrigation to plants during periods of drought. The unsettled weather conditions preceding the August survey in 2017 meant that summer water shortages due to drought had not been a particular issue for green roof vegetation. Nonetheless, significantly greater plug plant cover on non-Aquaten plots was an interesting result, and this would benefit from further investigation to verify whether the pattern was a consequence of the prevailing weather conditions and related to presence/absence of Aquaten, or whether this was merely an artefact of the experimental design.

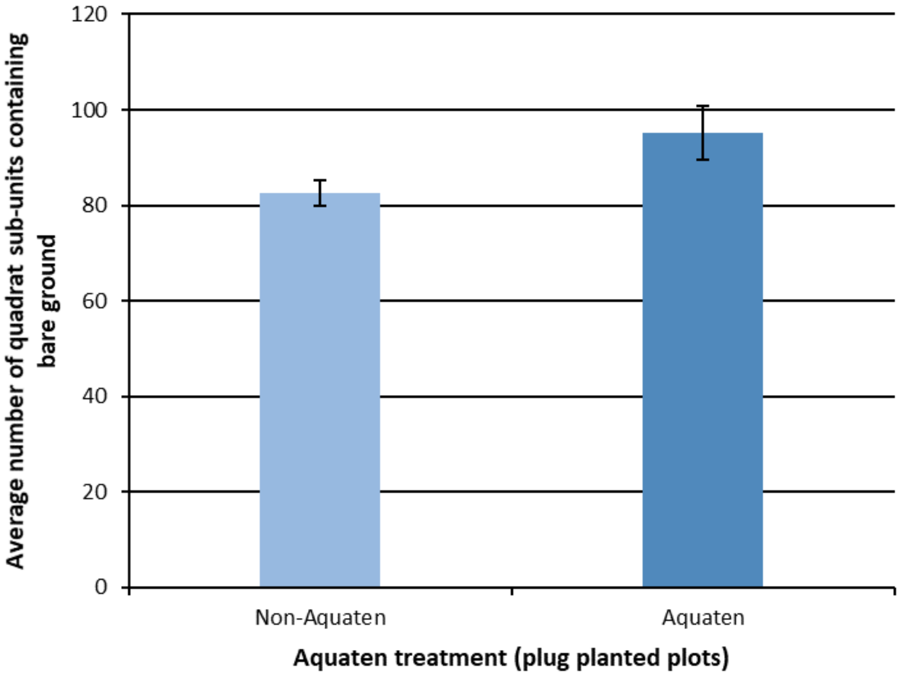


Figure 99. Average number of quadrat sub-units containing areas of bare ground on the Richard Knight House green roof, 11th August 2017. A lower proportion of bare ground equates to greater vegetation cover. Averages are calculated on the number of sub-units out of 100 sub-units within which bare ground was recorded for 18 quadrats for the two vegetation treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

As in June, vegetation cover was greatest in plots with the deepest substrate treatment (130 mm). However in contrast to June, a Kruskal-Wallis non-parametric test demonstrated this difference was now significant (p = 0.028 and Figure 100). Post-hoc Mann-Whitney U Exact two-tailed tests revealed that vegetation cover was significantly greater on the deepest 130 mm substrate, compared to the shallowest 50 mm plots (p = 0.005). There was, however, no significant difference between other substrate depths (130 mm versus 100 mm: p = 0.105; 50 mm versus 100 mm: p = 0.792). These results indicated that provision of deeper substrate layers could have been beneficial for vegetation cover and growth.

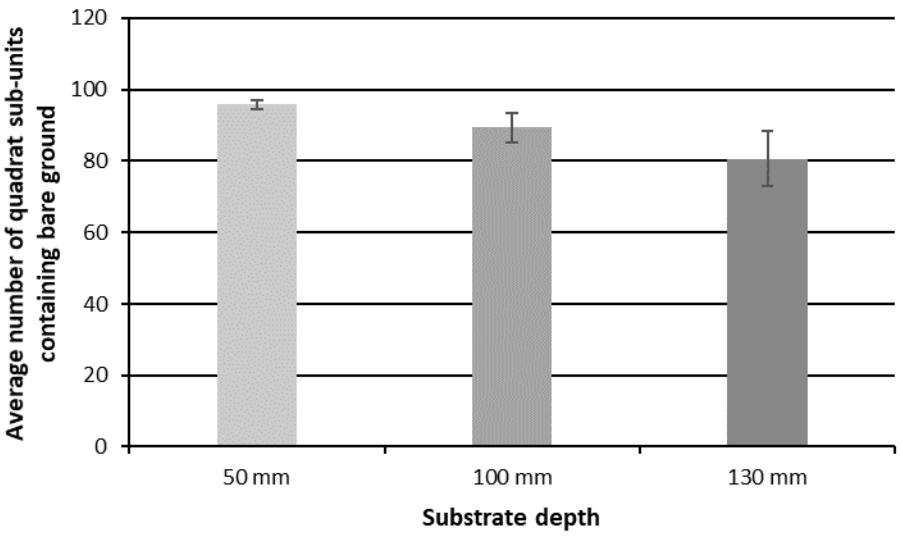


Figure 100. Average number of quadrat sub-units containing areas of bare ground at each substrate depth, Richard Knight House green roof, 11th August 2017. A lower proportion of bare ground equates to greater vegetation cover. Averages are calculated on the number of sub-units out of 100 within which bare ground was recorded for 12 quadrats in plots at the substrate depths 50 mm, 100 mm, and 130 mm. Error bars represent standard error of the mean.

Kruskal-Wallis non-parametric tests of vegetation cover at different substrate depths on the Aquaten and non-Aquaten areas revealed there was no significant difference within non-Aquaten plots (p = 0.875). As in June, however, there was a significant difference between substrate depths in Aquaten plots (p = 0.007). Vegetation cover was again highest in the 130 mm plots in Aquaten areas (Figure 101), and post-hoc Mann-Whitney U Exact two-tailed tests confirmed that this was significant (130 mm versus 50 mm: p = 0.005; 130 mm versus 100 mm: p = 0.030). There was no significant difference between 50 mm and 100 mm plots on Aquaten (p = 0.359). The continuation of this significant trend provided further evidence that combining the use of Aquaten and deeper substrates may enhance plant cover and growth. Nonetheless, further more controlled research would be useful to determine if this created conditions more favourable to grass growth, and whether this then had a detrimental impact on wildflower abundance.

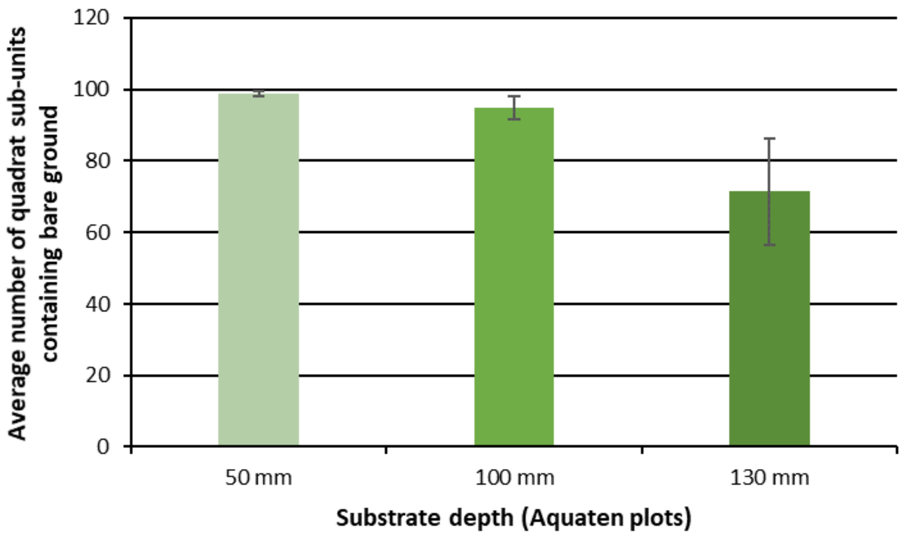


Figure 101. Average number of quadrat sub-units containing areas of bare ground on Aquaten plots at each substrate depth, Richard Knight House green roof, 11th August 2017. A lower proportion of bare ground equates to greater vegetation cover. Averages are calculated on the number of sub-units out of 100 sub-units within which bare ground was recorded for 6 quadrats in Aquaten plots at the substrate depths 50 mm, 100 mm, and 130 mm. Error bars represent standard error of the mean.

A Kruskal-Wallis non-parametric test was carried out comparing the vegetation cover on each test treatment to assess whether there was a significant difference. As in the previous survey, there was a significant difference when test plots when compared individually (p = 0.007), and again the greatest vegetation cover was recorded on an Aquaten plot with the deepest substrate treatment (130 mm) which was seeded. This plot continued to be dominated by the grass *F. rubra*.

Grass cover

Consistent with the findings in June, a greater proportion of grass cover was recorded on the seeded plots than on the plug planted plots (Figure 102), and a Mann-Whitney U Exact two-tailed test confirmed the difference was significant (p = 0.002). On average grass cover had slightly increased in plug planted plots, but had slightly decreased in seeded plots. By the second survey in 2016, grass cover in seeded plots had reduced substantially, and this was attributed to the drought conditions experienced that summer. The findings for the first two surveys in 2017 indicate that under favourable weather conditions, grass cover can remain fairly constant during summer.

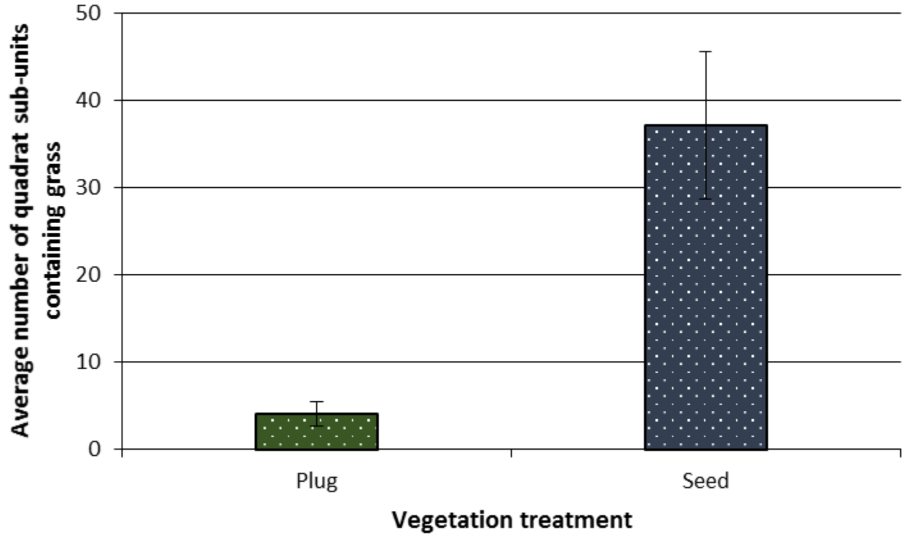


Figure 102. Average number of quadrat sub-units containing grass on the Richard Knight House green roof, 11th August 2017. Averages are calculated on the total number of records of all grass species within each quadrate within each experimental plot for 18 quadrats for the two vegetation treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

14th September 2017 survey

A final vegetation survey was carried out at Richard Knight House on the 14th September 2017. The weather conditions continued to be favourable for green roof plant growth, and again the vegetation on Richard Knight House green roof experimental plots was in a much healthier condition than was recorded during the survey in September 2016.

Floral species richness

Floral species richness was similar to the total for the August survey, with forty-eight species being recorded in the thirty-six 50 x 50 cm quadrats. This was much higher than the thirty-three species recorded during the previous year's survey in September 2016. This higher species richness and indeed the consistent levels of floristic species richness recorded throughout the surveys in 2017 was very likely a consequence of the more favourable summer weather conditions and the more established resilient vegetation. In total, four grass species were recorded in quadrats in September, with the remaining species being wildflowers. Consistent with the previous survey in August, and in contrast to the June findings, species richness was higher in seeded plots (Figure 103). Despite a more substantial difference between the seeded and plug planted treatments, a Mann-Whitney U Exact two-tailed test revealed that this was not significant (*p* = 0.067).

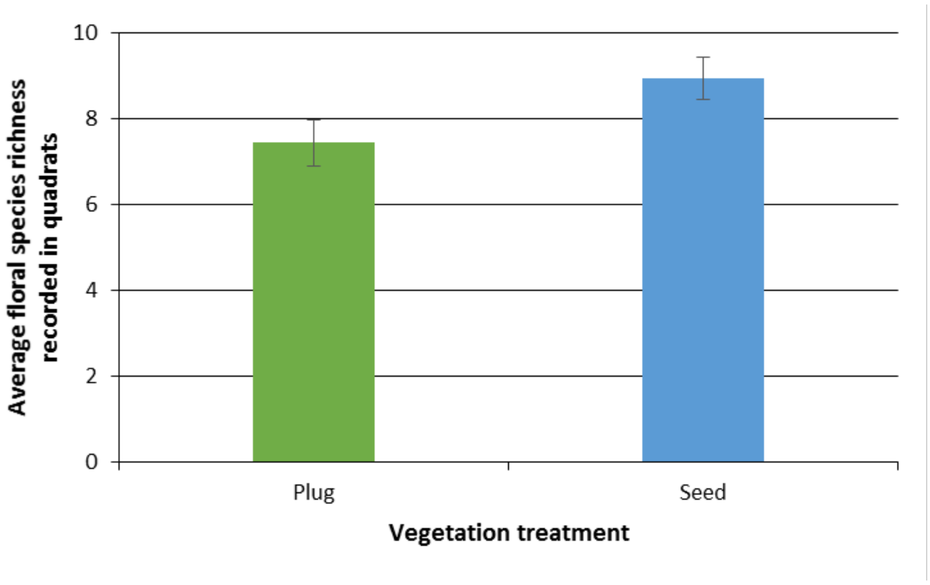


Figure 103. Average floral species richness on the Richard Knight House green roof, 14th September 2017. Averages are calculated on the number of floral species recorded in 18 quadrats for the two vegetation treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

Seeded species richness was greater in non-Aquaten plots (Figure 104), and a Mann-Whitney U Exact two-tailed test confirmed the difference was significant (*p* = 0.044). There was no significant difference in Aquaten plots (*p* = 374).

When vegetation treatments were analysed individually, species richness was higher in non-Aquaten areas, but this was not significant (seeded species on Aquaten versus non-Aquaten areas: *p* = 0.280; plug planted species on Aquaten versus non-Aquaten areas: *p* = 0.529). The trend for greater floristic richness on non-Aquaten plots for both vegetation treatments for August and September, whilst not significant, provided further indication that when weather conditions were favourable during the growing season, species richness appeared to be reduced in Aquaten areas. Nonetheless, the lack of randomised replication of individual treatments in this experiment means that further more rigorous investigation is needed to verify this pattern.

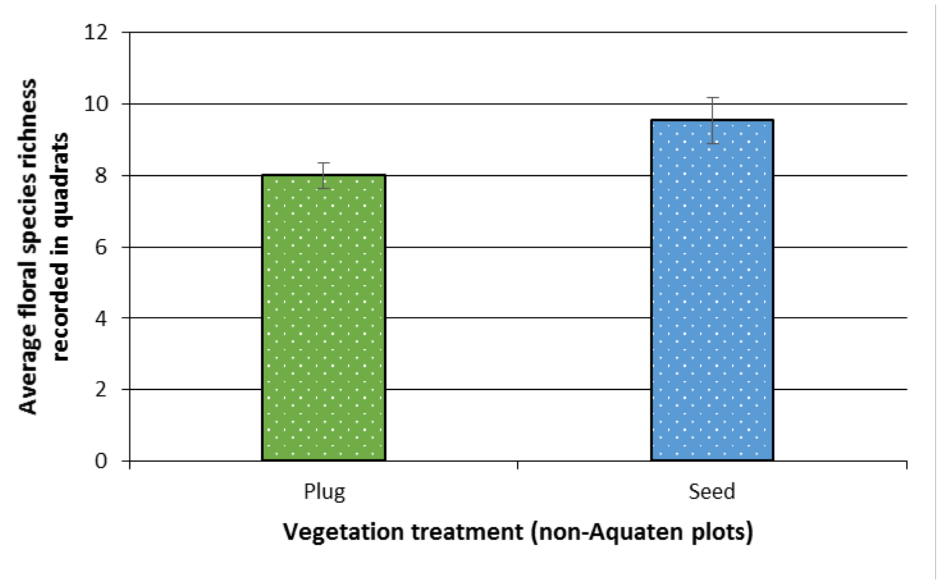


Figure 104. Average floral species richness in non-Aquaten plots on the Richard Knight House green roof, 14th September 2017. Averages are calculated on the number of floral species recorded in 9 quadrats on non-Aquaten plots for the two vegetation treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

Vegetation cover

In terms of colonisation of the plots and vegetation cover, the number of quadrat sub-units containing bare ground was used as a proxy for vegetation cover. In contrast to the previous two surveys, more bare ground was recorded on the seeded plots than the plug planted plots (Figure 105), indicating that vegetation cover was now more developed in the plug planted treatments. However, a Mann-Whitney U Exact two-tailed test demonstrated that this difference was not significant ($p = 0.066$). This result suggested that towards the end of the summer, plug planted species were growing more vigorously than seeded species.

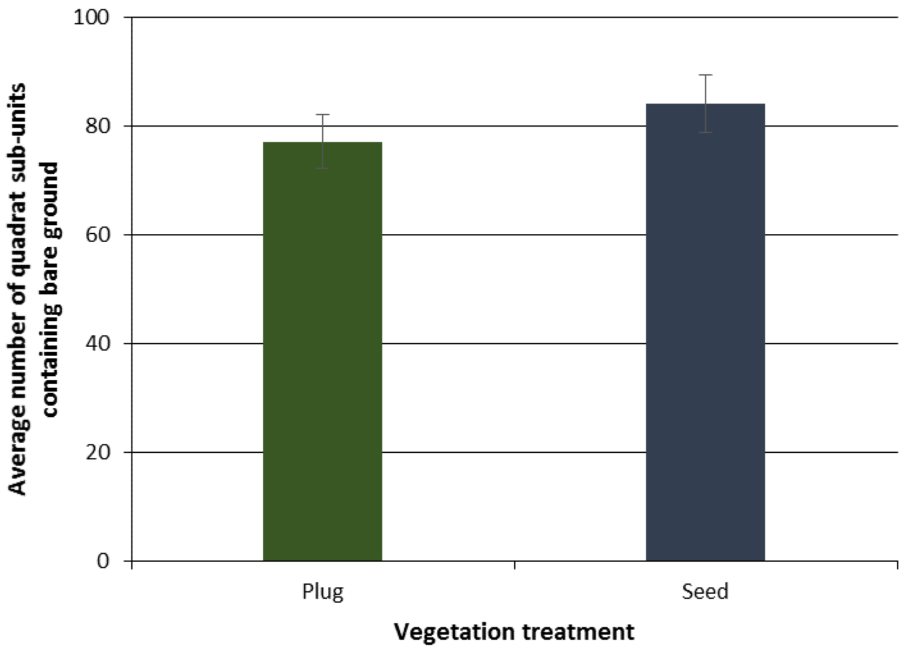


Figure 105. Average number of quadrat sub-units containing areas of bare ground on the Richard Knight House green roof, 14th September 2017. A lower proportion of bare ground equates to greater vegetation cover. Averages are calculated on the number of sub-units out of 100 sub-units within which bare ground was recorded for 18 quadrats for the two vegetation treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

Consistent with the findings in August, vegetation cover was greater in the plug planted plots on the non-Aquaten areas of the roof (p = 0.021 and Figure 106). A consistent pattern also continued for seeded plots whereby greater vegetation cover was recorded in the Aquaten areas, although this was not significant (p= 0.372). These contrasting results for vegetation cover for seeded and plug planted species on Aquaten areas could be related to the experimental design or the different growth patterns/spp mixes between pre-grown plug plants and seeded species. Further, more controlled, experimentation would be needed to understand these patterns in greater detail.

Consistent with the previous two surveys, vegetation cover was greatest in plots with the deepest (130 mm) substrate treatment (Figure 107). However, a Kruskal-Wallis non-parametric test demonstrated this difference was not significant (p = 0.07). Whilst the result was not significant, these findings provided further supporting evidence that deeper substrates appeared to produce enhanced vegetation growth and cover.

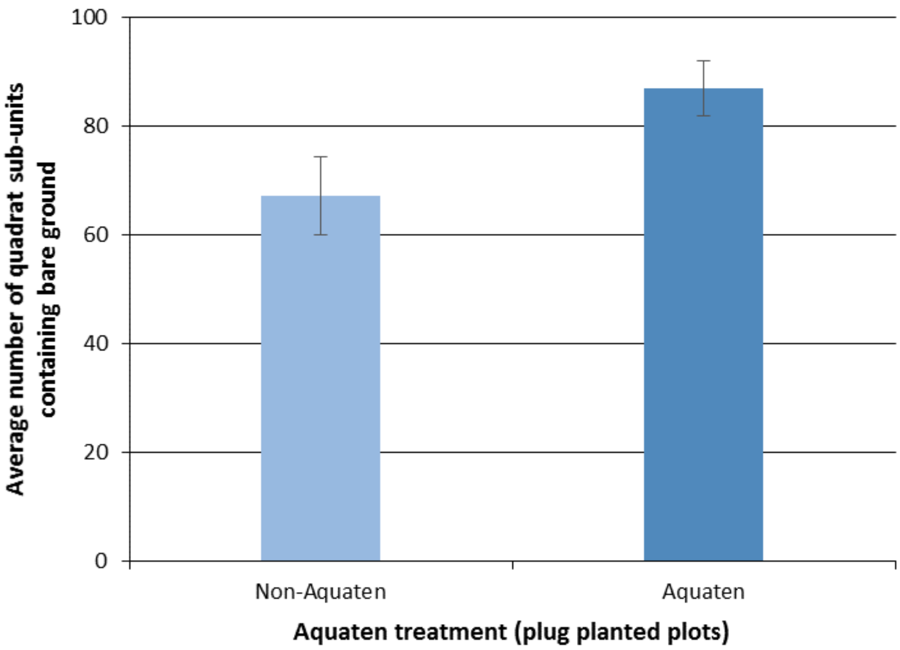


Figure 106. Average number of quadrat sub-units containing areas of bare ground on the Aquaten treatment for plug planted plots, Richard Knight House green roof, 14th September 2017. A lower proportion of bare ground equates to greater vegetation cover. Averages are calculated on the number of sub-units out of 100 sub-units within which bare ground was recorded for 9 quadrats for plug planted vegetation in Aquaten and non-Aquaten areas. Error bars represent standard error of the mean.

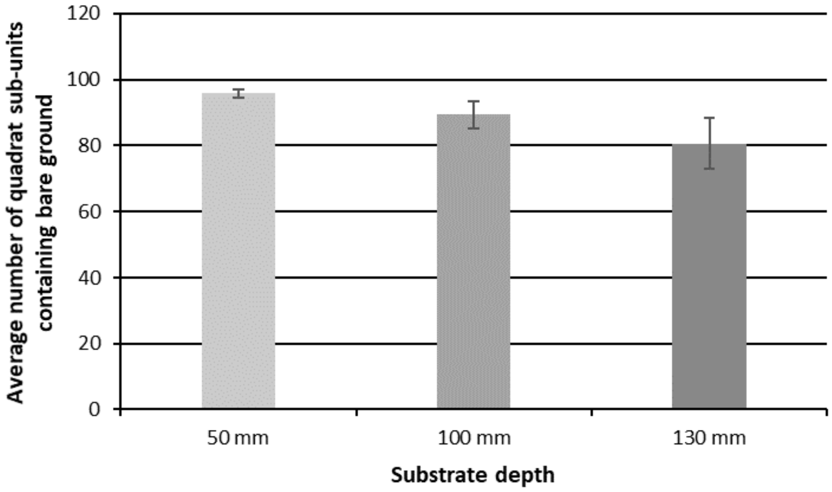


Figure 107. Average number of quadrat sub-units containing areas of bare ground at each substrate depth, Richard Knight House green roof, 14th September 2017. A lower proportion of bare ground equates to greater vegetation cover. Averages are calculated on the number of sub-units out of 100 within which bare ground was recorded for 12 quadrats in plots at the substrate depths 50 mm, 100 mm, and 130 mm. Error bars represent standard error of the mean.

Kruskal-Wallis non-parametric tests of vegetation cover at different substrate depths on the Aquaten and non-Aquaten areas revealed there was no significant difference within non-Aquaten plots (*p* = 0.884), but as in previous surveys, there was a significant difference between substrate depths in Aquaten plots (*p* = 0.013). Vegetation cover was again highest in 130 mm plots (Figure 108), and post-hoc Mann-Whitney U Exact two-tailed tests confirmed that there was a significant difference between 130 mm and 50 mm substrate depths on Aquaten (*p* = 0.007), but there was no significant difference between other depths on Aquaten (130 mm versus 100 mm: *p* = 0.149; 50 mm versus 100 mm plots: *p* = 0.101). The continuation of this pattern provided further supporting evidence that combining the use of Aquaten and deeper substrates may enhance plant cover and growth. Nonetheless, as previously stated, it would be useful to study this pattern with greater replication to understand whether this created diverse plant coverage and did not encourage dense grass growth at the expense of other wildflower species.

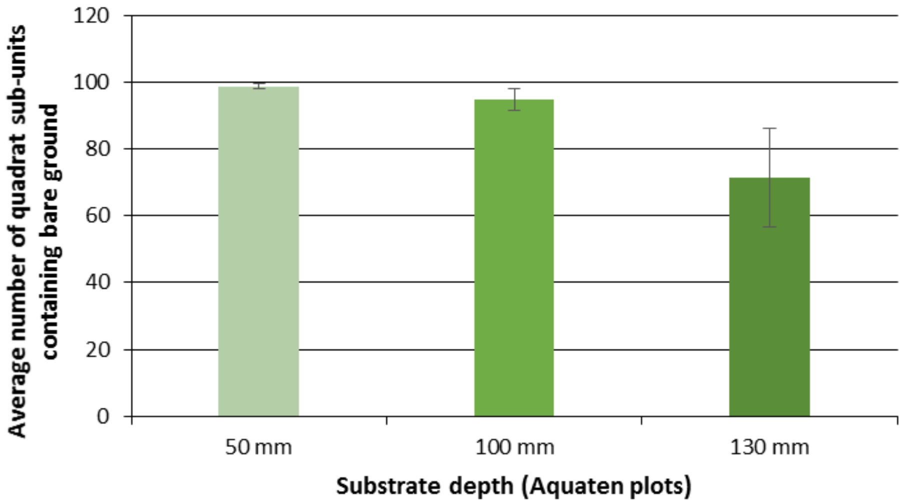


Figure 108. Average number of quadrat sub-units containing areas of bare ground at each substrate depth, Richard Knight House green roof, 14th September 2017. A lower proportion of bare ground equates to greater vegetation cover. Averages are calculated on the number of sub-units out of 100 within which bare ground was recorded for 12 quadrats in plots at the substrate depths 50 mm, 100 mm, and 130 mm. Error bars represent standard error of the mean.

A Kruskal-Wallis non-parametric test was carried out comparing the vegetation cover on each test treatment to assess whether there was a significant difference. Consistent with previous surveys, there was a significant difference when test plots when compared individually (*p* = 0.006). However, in contrast to previous surveys, the greatest vegetation cover was recorded on a non-Aquaten plot with the 100 mm substrate treatment which was plug planted. Also in contrast to the previous findings, vegetation cover in this plot was not predominantly characterised by grass, but instead this plot had become dominated by the wildflower kidney vetch *Anthyllis vulneraria*.

Grass cover

The pattern for the previous two surveys continued in September, and greater grass cover was recorded on the seeded plots than on the plug planted plots (Figure 109). A Mann-Whitney U Exact two-tailed test demonstrated that this difference between treatments was significant again (p = 0.004). Grass cover had increased slightly since the August survey for both types of vegetation treatment, indicating a steady increase in grass cover on plug planted plots, and a fairly constant level of grass cover on seeded plots throughout the summer. The contrast with grass cover patterns recorded in 2016 was presumably indicative of the slightly cooler and damper weather conditions during the summer of 2017, meaning that the grasses were less drought-stressed and so able to maintain a relatively consistent coverage.

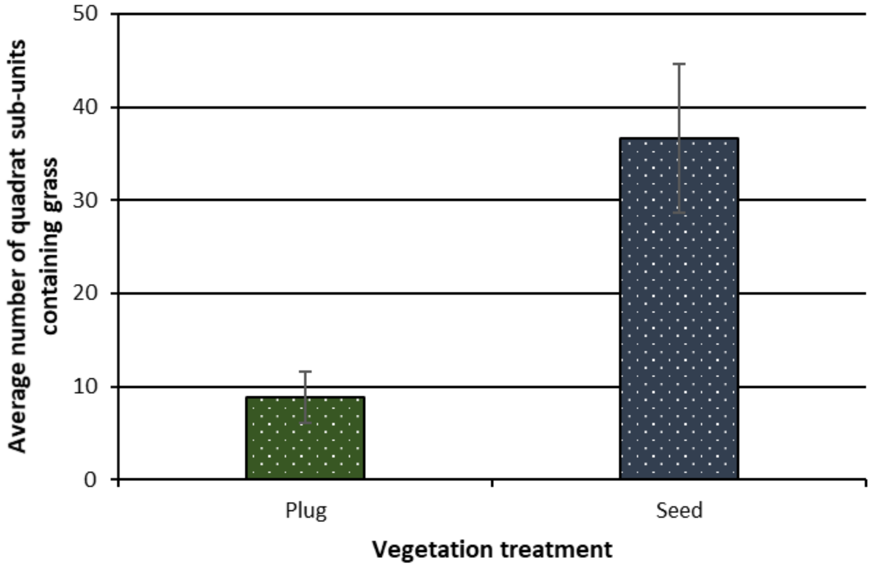


Figure 109. Average number of quadrat sub-units containing grass on the Richard Knight House green roof, 14th September 2017. Averages are calculated on the total number of records of all grass species within each quadrate within each experimental plot for 18 quadrats for the two vegetation treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

In addition to the quadrat monitoring, photographs were taken of the green roof to capture the typical cover during the 2017 monitoring period (Figures 110 and 111).

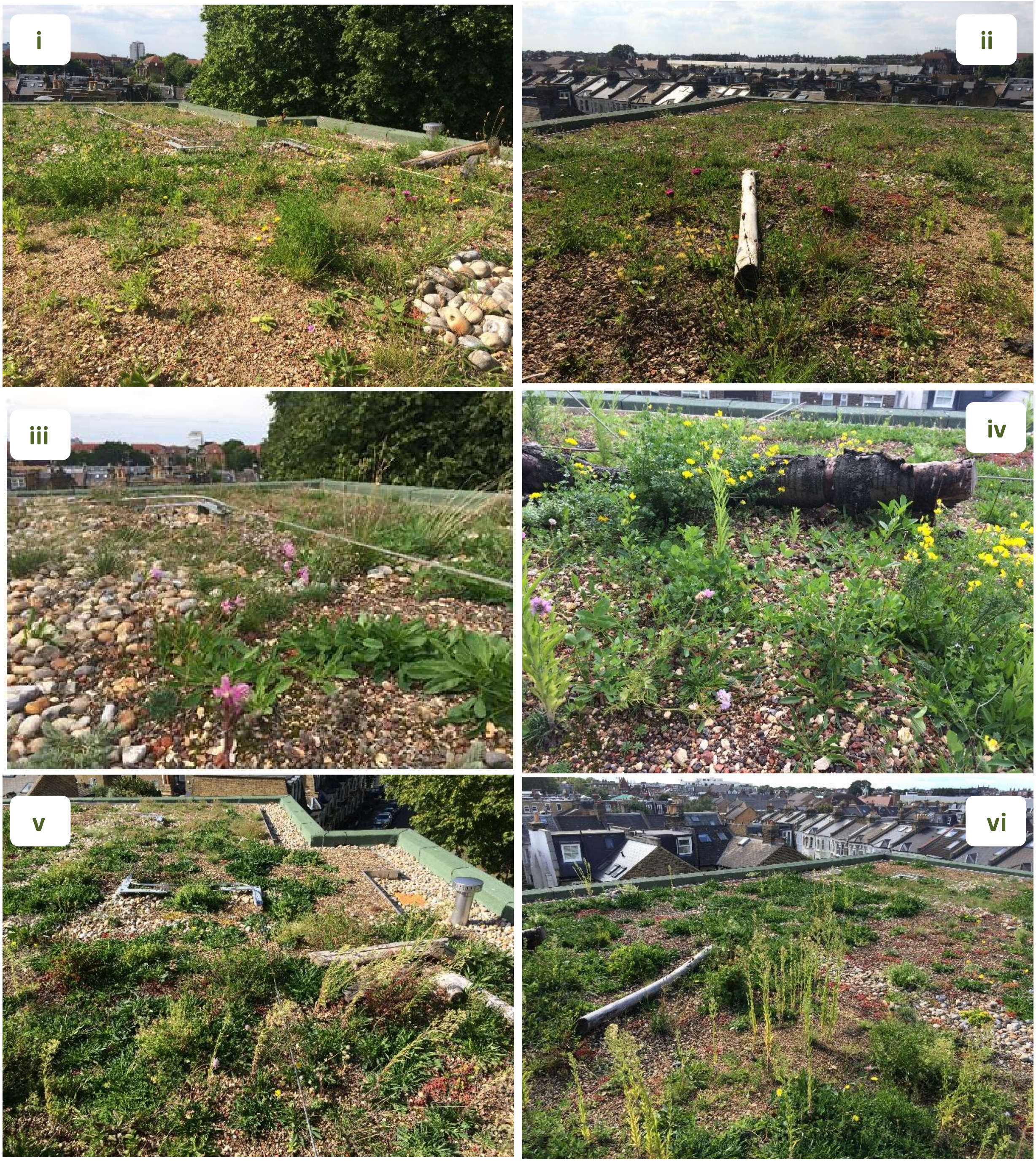


Figure 110. Images of vegetation development on Richard Knight House green roof, summer 2017. Images represent: i) 14th June 2017 view of west-facing side of roof looking north; ii) 14th June 2017 view of west-facing side of roof looking south; iii) 11th August 2017 view of west-facing side of roof looking north; iv) 11th August 2017 view of west-facing side of roof looking south; v) 14th September 2017 view of west-facing side of roof looking north; vi) 14th September 2017 view of west-facing side of roof looking south.

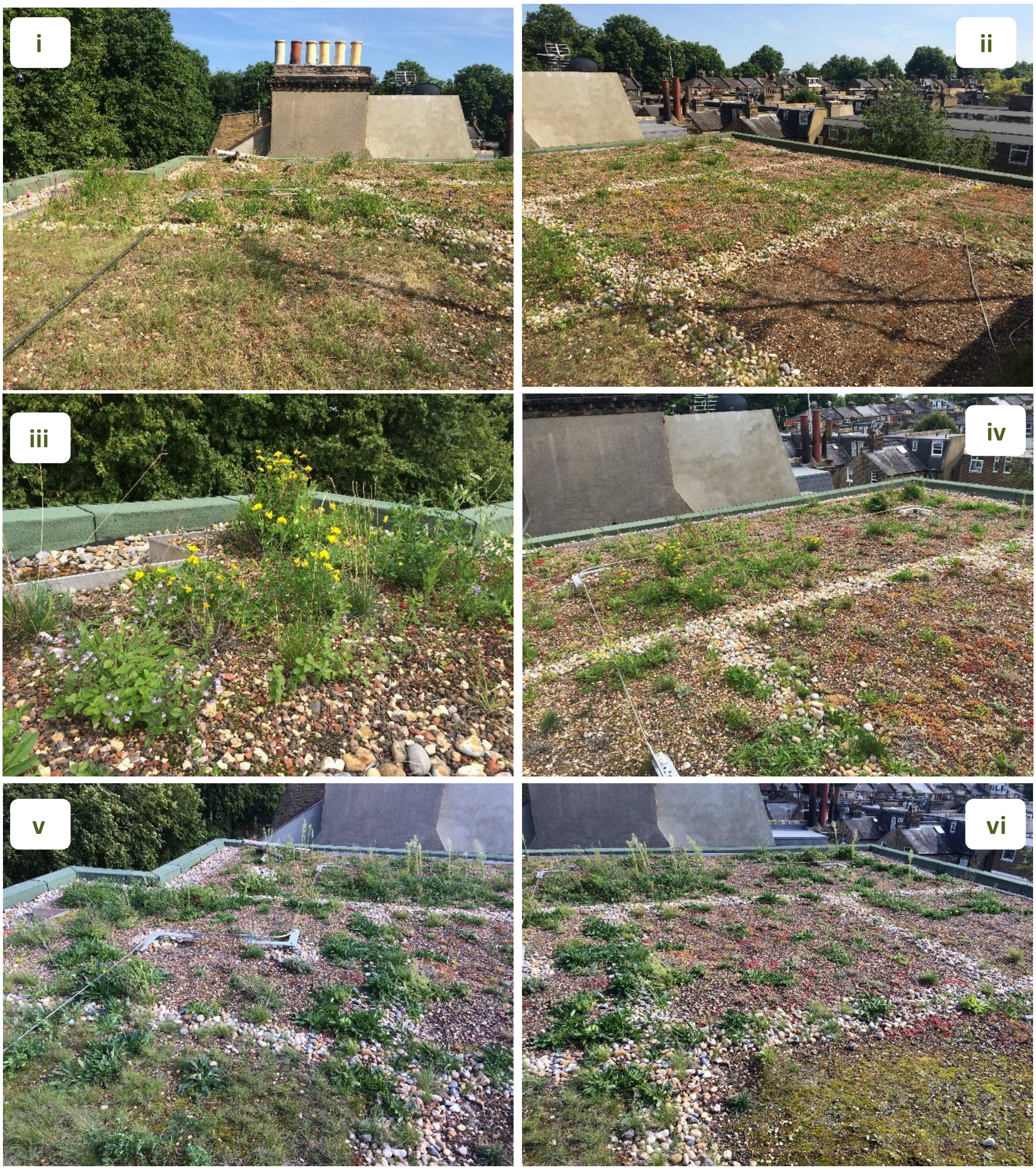


Figure 111. Images of vegetation development on Richard Knight House green roof, summer 2017. Images represent: i) 14th June 2017 view of east-facing side of roof looking north; ii) 14th June 2017 view of east-facing side of roof looking south; iii) 11th August 2017 view of east-facing side of roof looking north; iv) 11th August 2017 view of east-facing side of roof looking south; v) 14th September 2017 view of east-facing side of roof looking north; vi) 14th September 2017 view of east-facing side of roof looking south.

3.7 Photographic monitoring

In addition to the specific vegetation monitoring of the retrofitted green infrastructure, photos were taken to capture the development of the vegetation and wildlife visiting the sites. Below are a small selection of these images (Figures 112 and 113):

Figure 112. Images from green infrastructure retrofit project in Hammersmith. Clockwise from top left: Common carder bee (*Bombus pascuorum*) on birdsfoot trefoil in a swale at Queen Caroline Estate; Pram shed green roof from above showing gravel drainage channels at Queen Caroline Estate; Iris in flower in the Richard Knight House rain garden; and Ox-eye daisies in flower in a SuDS basin at Queen Caroline Estate.

Figure 113. Images from green infrastructure retrofit project in Hammersmith. Clockwise from top left: Hairy-footed flower bee (*Anthophora flumipes*) foraging on apple blossom at Richard Knight House; Birdsfoot trefoil growing next to deadwood log on Richard Knight House green roof; Vertical rain garden in full bloom at Queen Caroline Estate; Solitary bee on birdsfoot trefoil at Queen Caroline Estate; Umbellifer in bloom at Queen Caroline Estate; Red admiral butterfly on buddleia in rain garden at Queen Caroline Estate; Rain garden in full bloom at Cheeseman Terrace.

3.8 Monitoring in relation to performance indicators

Reduction in surface water run-off & reduction in run-off from green roofs

Based on the data captured from the weather stations, the time-lapse cameras, the v-notch sensors and the pressure sensor, it is possible to calculate an approximate volume of rain that has been diverted from otherwise entering the storm drain system by the interventions installed across the estates during this initial monitoring period. This estimation was carried out by calculating the total rainfall that had fallen on each of the estates during the period 1st October 2016 to 30th September 2017:

- Richard Knight House = 551.4 mm

- Queen Caroline Estate (and Cheeseman Terrace) = 606.2 mm

The total catchment areas of the SuDS interventions at each site:

- Richard Knight House = 258.5 m² ground level SuDS and 244.5 m² of green roofs

- Queen Caroline Estate = 1305.5 m² ground level SuDS and 129.75 m² of green roofs

- Cheeseman Terrace = 310 m² ground level SuDS

Then multiplying the rainfall by the area of the SuDS interventions based on:

- the evidence that the capacity of the ground level SuDS at Richard Knight House and Queen Caroline Estate were never exceeded (and they therefore **diverted <u>100%</u> of the rainfall away from the storm drain system**);

- the evidence that the capacity of the ground level SuDS at Cheeseman Terrace was only rarely exceeded with controlled release to the combined sewer system (and **diverted an approximate <u>95%</u> of the rainfall away from the storm drain system**);

and

- **that green roofs absorbed an average of <u>82.8%</u> of rainfall landing on them** (a conservative estimate based on the average attenuation for the five largest winter and summer storm events analysed for the pramshed green roofs).

This provided a total value of <u>1,220,904 Litres</u> of rainfall retained and thus diverted away from the storm drain system by the interventions during the initial monitoring period.

N.B. it must be noted that this is a rough estimate based on monitoring thus far and several caveats must be attached to this value. Firstly, values for the green roofs were based on the performance during the largest rain events and their performance during smaller events (that made up the majority of the events) would be expected to be better than the 82.8% threshold. Secondly, values for the Richard Knight House green roof used the same retention values as those for the pram shed roofs, although it is likely that the Richard Knight House green roof would have better retention potential (monitoring has not yet been possible due to lack of access to downpipes). The estimate also assumed that all rainfall falling within the catchment areas had been diverted to the SuDS features (and thus that all guttering was functioning correctly). Lastly, v-notch weirs are less precise at low flow rates, so run off at low flow rates over long time periods from the roofs may be inaccurate. However, high flow rates would have a greater degree of accuracy and these are the rates of most importance related to storm drain overload.

Reduction in ambient temperature

Calculation of the reduction in ambient temperatures across the entire estates due to green infrastructure interventions was not possible from the results of this study due to the scale of monitoring that would have been needed and the scope of the monitoring remit for delivering this study. Moreover, the majority of research associated with the effect of urban green infrastructure on the urban heat island effect and urban heat stress indicates that the effects of small-scale green interventions are typically quite localised (Eisenberg et al. 2015) with as little distance as two metres away from a green structure being enough for the cooling effects to be lost (Connp et al. 2016) and a substantial net increase of greenspace within a city being needed in order to reduce ambient temperatures across an area. For example, Gill et al. (2007) suggested that a 10% increase in the area of green infrastructure in Greater Manchester (in areas with little or no green cover) would be required for ambient temperatures to be cooled by up to 2.5°C under the high emissions scenarios based on UKCP02 predictions (DoE 1996; UKCIP 2001).

Nevertheless, some quantifiable benefits of the green infrastructure interventions were captured and would have been expected to provide benefits to local residents when in the vicinity of the green infrastructure interventions. This included temperature reductions recorded from thermal cameras of:

- A maximum of a 39.4% reduction in temperature on a vegetated green roof compared to surrounding grey infrastructure

- A maximum of a 44.1% reduction in temperature on a vegetated green roof compared to surrounding flat roof areas

- A maximum of a 18.6% reduction in temperature in a swale compared to surrounding grey infrastructure

- A maximum of a 43.0% reduction in temperature between a rain garden and surrounding grey infrastructure

- A maximum of a 31. 5% reduction in temperature between a SuDS basin and surrounding grey infrastructure

- A maximum of a 29.8% reduction in temperature between a vertical rain garden and control brick wall

- A maximum of a 6.8% or 1.6°C reduction in heat stress between a vertical rain garden and control brick wall

These results corresponded closely with those recorded in the previous monitoring period.

Reduction in surface water pollution

In addition to stormwater management benefits, there is evidence to suggest that the use of green infrastructure SuDS components can also provide surface water pollution benefits in urban areas (Ellis et al. 2012). This comprises improving the water quality associated with urban pollutants such as hydrocarbons in road run-off. There is less consensus in published literature on the effects that green roofs can have on water quality (Berndtsson 2010), with research indicating that effects can vary dependent upon the age of the roof (i.e. newly installed versus established) and the water quality entering the roof (i.e. direct rainfall versus scrubbing of urban pollutants from rooftops).

In relation to this study, ground level SuDS systems created **an almost 100% improvement in surface water pollution**. As, with exception of small volumes at Cheeseman Terrace, no surface water was recorded leaving any of the designed elements and feeding into the combined sewer system.

No monitoring of water quality from green roofs was carried out as it was decided that water quality would reflect the newly-installed state of the roofs rather than a mature performance and would thus merely capture an initial flushing of nutrients from the roofs following installation (based on experience from the Barking Riverside green roof experiment (Connop et al. 2013). However, with an average reduction in runoff from the largest rain events of 82.8%, even if there remained some nutrient flushing from the green roofs, it would be expected that overall nutrient loading would be reduced compared to standard flat roofs.

Increase in vegetation cover

With the installation of the vertical rain garden and some other new rain gardens, vegetation cover at Queen Caroline Estate had a net increase again during this monitoring period.

Increase in biodiversity of selected groups when conventional amenity vegetation is compared with a biodiverse treatment (%)

In relation to quantifying the increase in biodiversity of selected groups when compared to amenity vegetation, an example of the biodiverse habitat created across the sites included the biodiverse green roof at Richard Knight House. In addition to creating habitat piles containing deadwood and sand mounds for ground nesting bees and wasps, this year 57 species of plant were recorded on the roof. This represented a slight decline compared to the 64 species recorded in the previous year, but this would be expected as the roof matures and bare areas decrease providing fewer opportunities for plants to colonise. Compared to if the roof were a standard flat roof**,** however, **this comprised a net increase of <u>57 floral species</u>**. Compared to a typical amenity lawn area this comprised an **increase of <u>47 floral species</u> or a <u>459%</u> increase** (based on floral surveys carried out on typical amenity lawn areas as part of a Barking Riverside landscaping study (Connop et al 2014) and a UEL campus biodiversity study (Connop et al 2012) giving an average number of floral species as 10.24 (*n = 42*)).

In addition to the floral increase, numerous invertebrate groups such as bees and spiders continued to be observed using both the structure and wildflower diversity of the ground level and roof level landscaping that were not observed using the surrounding amenity grass landscaping (see section 3.7 in this report and the other monitoring period reports (Connop and Clough 2016; Connop et al. 2016).

4. References

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Appendix A

A1 - Additional fixed-point camera images from winter events

Winter - Event 3

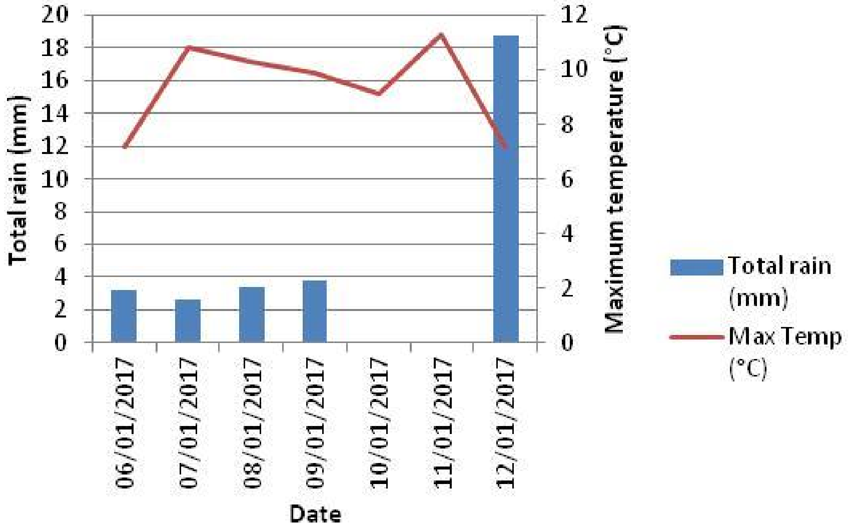
The third largest rain event (defined as mm of rain per 24 hr period) was on the 12th January 2017. For this rain event, a total of 16 mm of rain was recorded falling at Henrietta House and 18.8 mm of rain at Richard Knight House.

At Richard Knight House, this was a more intense rain event with the majority falling during an hour and a half period. The weather preceding the event was also fairly damp (Figure 114). The highest volume and intensity of rainfall during this event fell between 16:00 and 17:00, with the highest rain volume of 6 mm in an hour and the highest rain rate recorded as 9 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

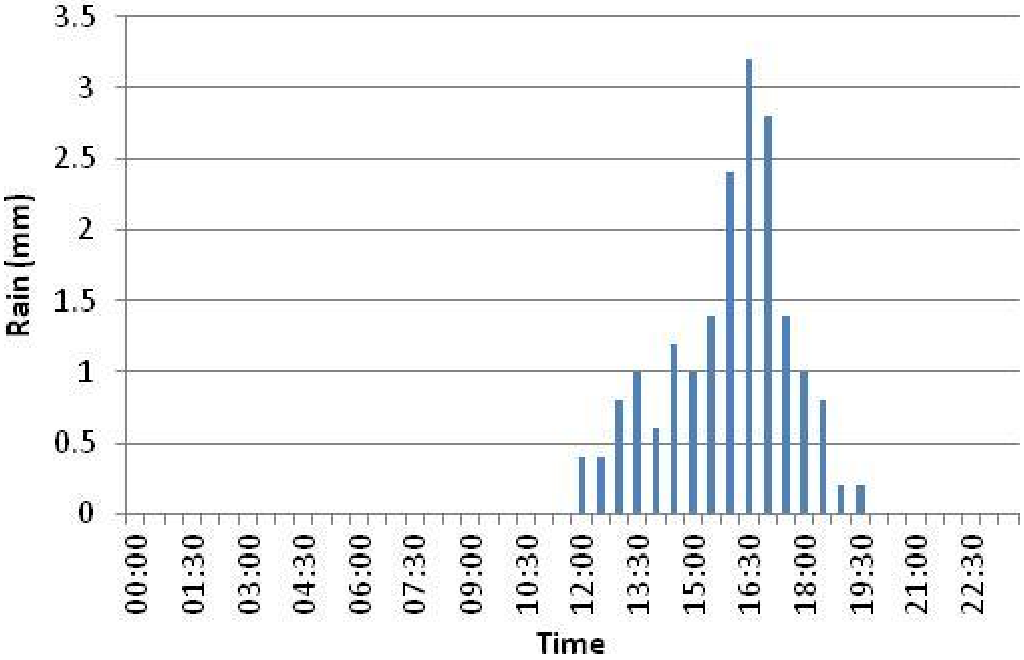
The time-lapse camera recorded the performance of the SuDS feature at Richard Knight House during this prolonged rain event on the 12th January 2017.

Richard Knight House rain garden (FPC4) performance during 18.8 mm rain event on 12th January 2017

A complete collection of the images from the Richard Knight House rain garden during the rain event from 11:30 to 20:00 on the 12th January 2017 were captured and analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 16:20 during the peak of the rainfall, despite substantial input from the neighbouring roofs, there was no obvious standing water within or around the rain garden (Figure 115.i). By the time of the end of the rain event at 19:45, there was also no obvious pooled water (Figure 115.ii) indicating that the rain garden was infiltrating all of the stormwater.



i)



ii)

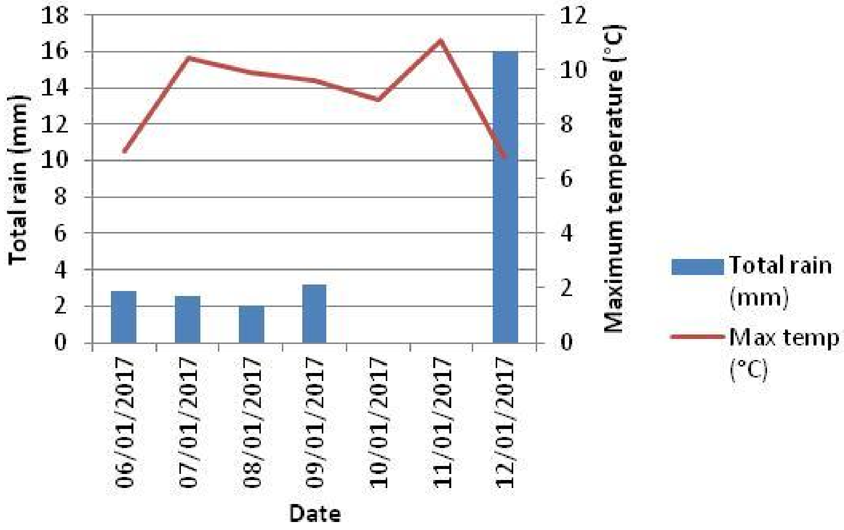
Figure 114. Details of rain event on the 12th January 2017 at Richard Knight House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes

Figure 115. Time-lapse camera images from Richard Knight House rain garden (FPC5), 12/01/2017. Images show i) no evidence of overflowing during period of highest rain intensity at 16:20 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 19:45 on the same day.

At Henrietta House, a similar pattern of a more intense rain event preceded by damper weather was recorded (Figure 116). The highest volume and intensity of rainfall during this event fell between 16:00 and 17:00, with the highest rain volume of 5.2 mm in an hour and the highest rain rate recorded as 9.2 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as 'slight', 'moderate', 'heavy', or 'violent' for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse cameras at Queen Caroline Estate and Cheeseman Terrace recorded the performance of the SuDS features during this prolonged rain event on the 12th January 2017.

i)



ii)

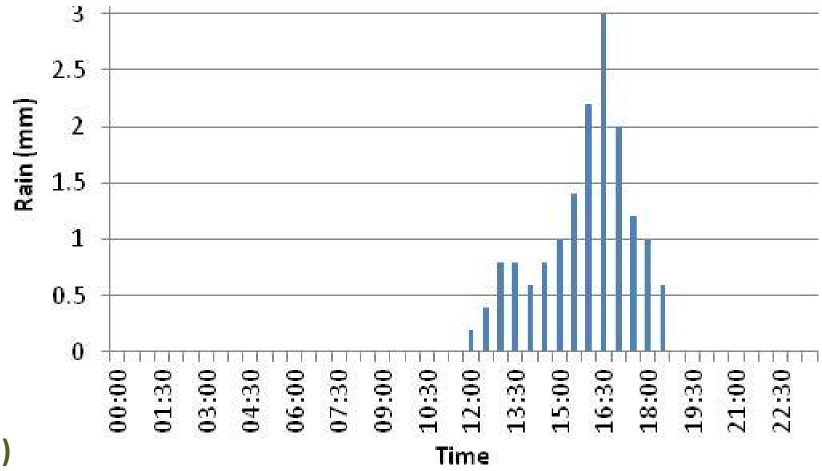


Figure 116. Details of rain event on the 12th January 2017 at Henrietta House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

Alexandra House swale (FPC1) performance during 16 mm rain event on 12th January 2017

A complete collection of the images from the Alexandra House swale during the rain event from 11:30 to 20:00 on the 12th January 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 16:20 during the peak of the rainfall, despite substantial input from the neighbouring roof, there was no obvious standing water within or around the rain garden (Figure 117.i). By the time of the end of the rain event at 20:00, there was also no obvious pooled water (Figure 117.ii) indicating that the swale was infiltrating all of the stormwater.

i)

Figure 117. (see below)

ii)

Figure 117. Time-lapse camera images from Alexandra House swale (FPC1), 12/01/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 16:22 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 19:58 on the same day.

Community Hall and Sofia House basins (FPC2) performance during 16 mm rain event on 12th January 2017

A complete collection of the images from the community hall and Sofia House basins during the rain event from 11:30 to 20:00 on the 12th January 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 17:20 during the peak of the rainfall, despite substantial input from the community hall roof, there was no obvious standing water within or around the basins (Figure 118.i). Following the cessation of the event at 20:00, there was also no obvious pooled water (Figure 118.ii) indicating that the basins were infiltrating all of the stormwater.

Figure 118. Time-lapse camera images from Community Hall and Sofia House basins (FPC2), 12/01/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 17:22 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 20:03 on the same day.

Adella House grass and stoney basins (FPC3) performance during 16 mm rain event on 12th January 2017

A complete collection of the images from the Adella House basins during the rain event from 11:30 to 20:00 on the 12th January 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 17:35 during the peak of the rainfall, despite substantial input from the Adella House roof, there was no obvious standing water within or around the basins (Figure 119.i). Following the cessation of the event at 20:00, there was also no obvious pooled water (Figure 119.ii) indicating that the basins were infiltrating all of the stormwater.

i)

Figure 119. (see below)

ii)

Figure 119. Time-lapse camera images from Adella House grass and stoney basins (FPC3), 12/01/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 17:35 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 20:01 on the same day.

Beatrice House swale (FPC4) performance during 16 mm rain event on 12th January 2017

A complete collection of the images from Beatrice House swale during the rain event from 11:30 to 20:00 on the 12th January 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 16:35 during the peak of the rainfall, despite substantial input from the Beatrice House roof, there was no obvious standing water within or around the swale (Figure 120.i). Following the cessation of the event at 20:00, there was also no obvious pooled water (Figure 120.ii) indicating that the basins were infiltrating all of the stormwater.

Figure 120. Time-lapse camera images from Beatrice House swale (FPC4), 12/01/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 16:34 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 20:07 on the same day.

Cheeseman Terrace rain gardens (FPC6) performance during 16 mm rain event on 12th January 2017

A complete collection of the images from Cheeseman Terrace rain gardens during the rain event from 11:30 to 20:00 on the 12th January 2017 were captured and analysed. They demonstrated that the rain gardens were able to retain and attenuate all of the rainfall that fell directly onto the area. Due to the design of the underdrainage from the road, analysis of pressure sensor data is required in order to establish whether all of the runoff from the road was also managed. Nevertheless, the images also demonstrated that at around 16:35 during the peak of the rainfall, there was no obvious standing water within or around the rain gardens (Figure 121.i). Following the cessation of the event at 20:00, there was also no obvious pooled water (Figure 121.ii) indicating that the rain gardens were not becoming saturated with stormwater.

i)

Figure 121. (see below)

ii)

Figure 121. Time-lapse camera images from Cheeseman Terrace rain gardens (FPC6), 12/01/2011. Images show i) no evidence of overflowing during a period of high rain intensity at 16:37 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 20:07 on the same day. N.B. the date displayed on the images does not correspond with the date of the rain event. This was due to a labelling error on the cameras. The actual data of the image was 12/01/2017.

Winter - Event 4

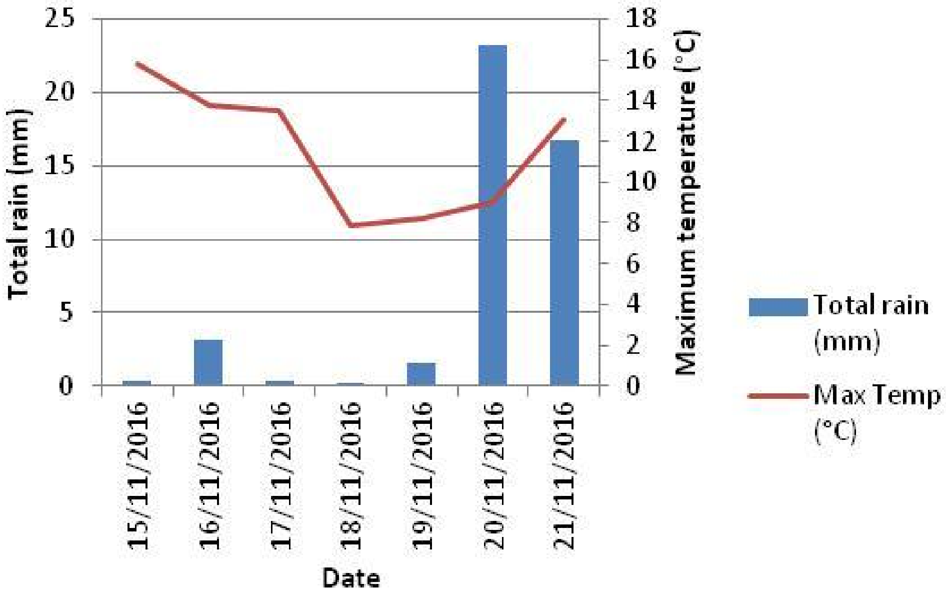
The next largest rain event (defined as mm of rain per 24 hr period) was on the 21st November 2016. For this rain event, a total of 15 mm of rain was recorded falling at Henrietta House and 16.8 mm of rain at Richard Knight House.

At Richard Knight House, this rain event was intermittent all day but with the peak rainfall falling during a half period. The rain event occurred a day after the second largest rain event of the monitoring period (Figure 122). As such, the ground would be expected to be fairly saturated. The highest volume and intensity of rainfall during this event fell between 18:00 and 19:00, with the highest rain volume of 4.8 mm in an hour and the highest rain rate recorded as 87.2 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

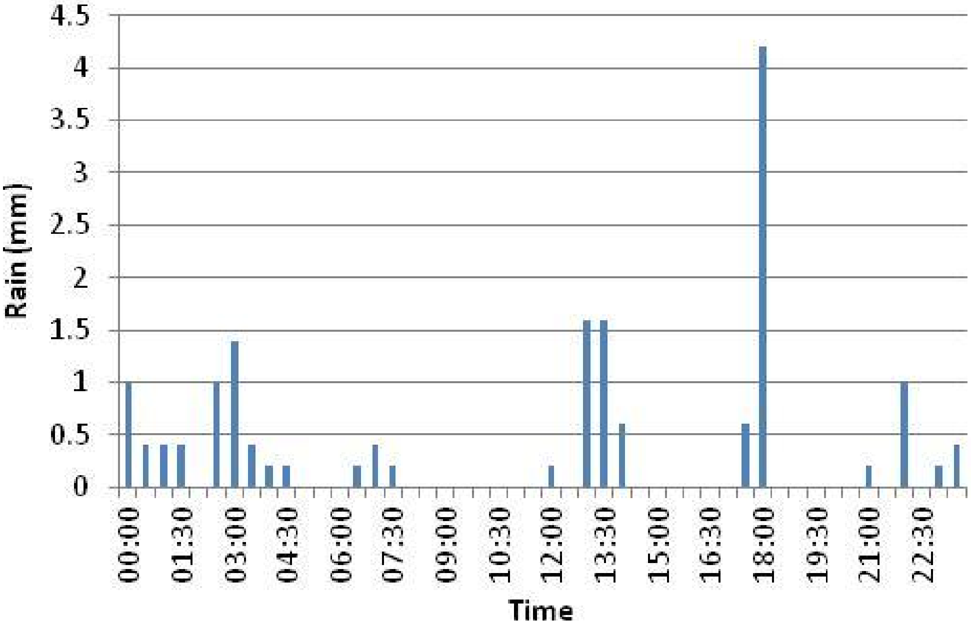
The time-lapse camera recorded the performance of the SuDS feature at Richard Knight House during this prolonged rain event on the 21st November 2016.

Richard Knight House rain garden (FPC4) performance during 16.8 mm rain event on 21st November 2016

A complete collection of the images from the Richard Knight House rain garden during the rain event from 00:01 to 23:59 on the 21st November 2016 were captured and analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images demonstrated that at around 18:45 during the peak of the rainfall, despite the channel supplying the rain garden becoming overloaded, there was no obvious standing water overflowing the bottom end of the rain garden, indicating that it was no filled to capacity (Figure 123.i). By the time of the end of the rain event at 23:59, there was also no obvious pooled water (Figure 123.ii) indicating that the rain garden was infiltrating all of the stormwater.



i)



ii)

Figure 122. Details of rain event on the 21st November 2016 at Richard Knight House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

i)

ii)

Figure 123. Time-lapse camera images from Richard Knight House rain garden (FPC5), 21/11/2016. Images show i) no evidence of overflowing during period of highest rain intensity at 18:42 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 23:59 on the same day.

At Henrietta House, a similar pattern of prolonged rain event with a peak rainfall intensity period was recorded (Figure 124). In contrast to Richard Knight House, the highest volume and intensity of rainfall during this event fell between 13:00 and 14:00, with the highest rain volume of 2.6 mm in an hour and the highest rain rate recorded as 11.2 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse cameras at Queen Caroline Estate and Cheeseman Terrace recorded the performance of the SuDS features during this prolonged rain event on the 21st November 2016.

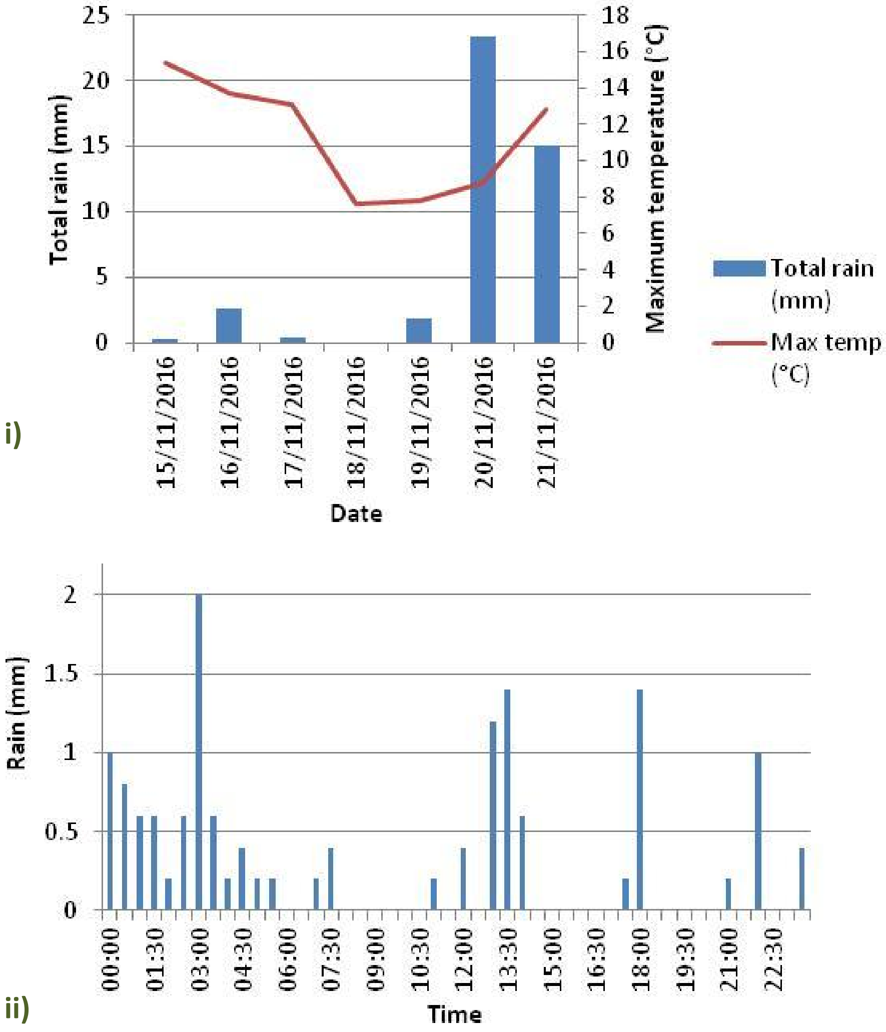


Figure 124. Details of rain event on the 21st November 2016 at Henrietta House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

Alexandra House swale (FPC1) performance during 15 mm rain event on 21st November 2016

No images were available for the 21st November 2016 rain event for this camera as there was a battery failure.

Community Hall and Sofia House basins (FPC2) performance during 15 mm rain event on 21st November 2016

A complete collection of the images from the community hall and Sofia House basins during the rain event from 00:01 to 23:59 on the 21st November 2016 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 13:50 during the peak of the rainfall, despite substantial input from the community hall roof, there was no obvious standing water within or around the basin (Figure 125.i). Following the more substantial part of the prolonged rain event at 16:45, there was also no obvious pooled water (Figure 125.ii) indicating that the basins were infiltrating all of the stormwater.

i) Figure 125. (see below)

ii)

Figure 125. Time-lapse camera images from Community Hall and Sofia House basins (FPC2), 21/11/2016. Images show i) no evidence of overflowing during a period of high rain intensity at 13:52 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 16:46 on the same day.

Adella House grass and stoney basins (FPC3) performance during 23.4 mm rain event on 20th November 2016

A complete collection of the images from Adella House basins during the rain event from 00:01 to 23:59 on the 21st November 2016 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 14:15 during the peak of the rainfall, despite substantial input from the Adella House roof, there was no obvious standing water within or around the basin (Figure 126.i). Following the prolonged rain event at 23:55, there was also no obvious pooled water (Figure 126.ii) indicating that the basins were infiltrating all of the stormwater.

i)

ii)

Figure 126. Time-lapse camera images from Adella House grass and stoney basins (FPC3), 21/11/2016. Images show i) no evidence of overflowing during a period of high rain intensity at 14:13 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 23:55 on the same day.

Beatrice House swale (FPC4) performance during 23.4 mm rain event on 20th November 2016

No images were available for the 20th November 2016 rain event for this camera as there was a battery failure.

Cheeseman Terrace rain gardens (FPC6) performance during 23.4 mm rain event on 20th November 2016

Due to delays in finalising the new monitoring scope, time-lapse cameras were not installed at Cheeseman Terrace on this date.

Winter - Event 5

The last substantial winter rain event analysed was on the 27th February 2017. For this rain event, a total of 12.8 mm of rain was recorded falling at Henrietta House and 16 mm of rain at Richard Knight House.

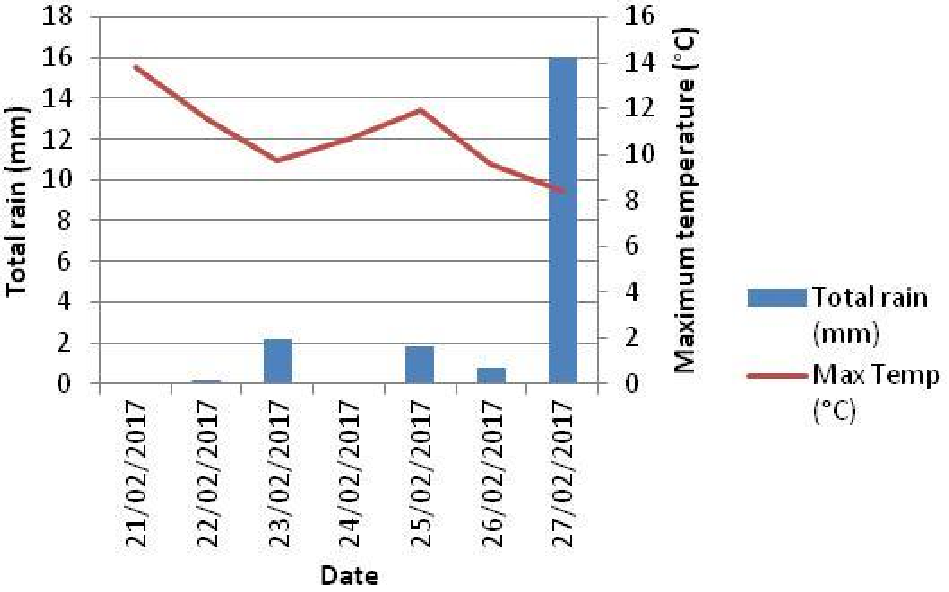
At Richard Knight House, this rain event was intermittent all day but with the majority of rain falling during two spells during the day. The weather preceding the rain event was damp but with no substantial rain events (Figure 127). The highest intensity of rainfall during this event fell between 10:30 and 11:30, with a rain volume of 2.6 mm in an hour and the highest rain rate recorded as 30.8 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse camera recorded the performance of the SuDS feature at Richard Knight House during this prolonged rain event on the 21st November 2016.

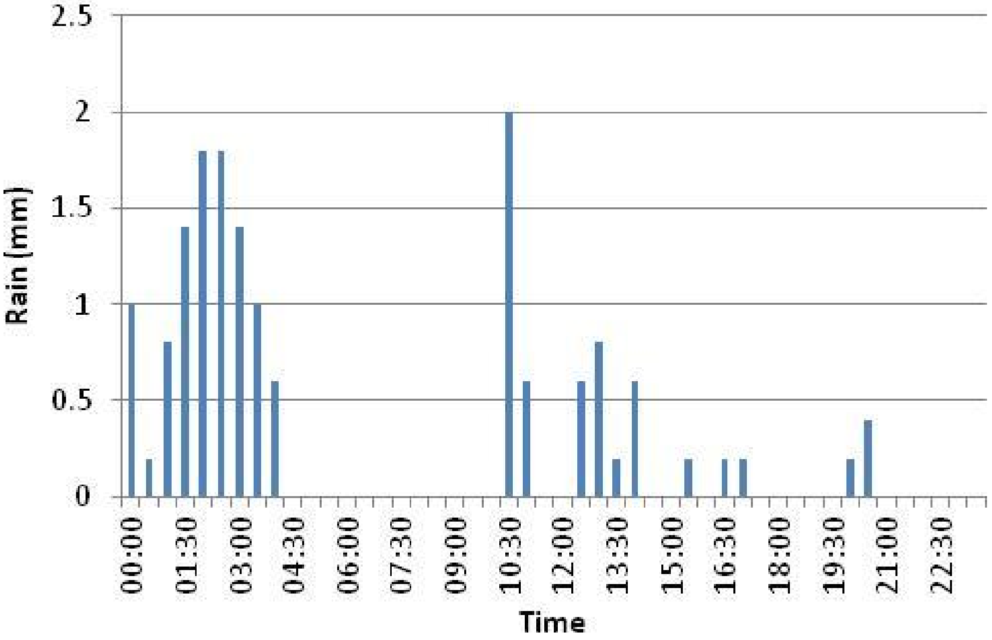
Richard Knight House rain garden (FPC4) performance during 16.8 mm rain event on 21st November 2016

A complete collection of the images from the Richard Knight House rain garden during the rain event from 00:01 to 21:00 on the 27th February 2017 were captured and analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images demonstrated that at around 03:40 during the peak of the first rainfall, there was no obvious standing water overflowing the bottom end of the rain garden, indicating that it was no filled to capacity (Figure 128.i). At the time of the second, more intense, rain event at

10:20, there was also no obvious pooled water (Figure 128.ii) indicating that the rain garden was infiltrating all of the stormwater.

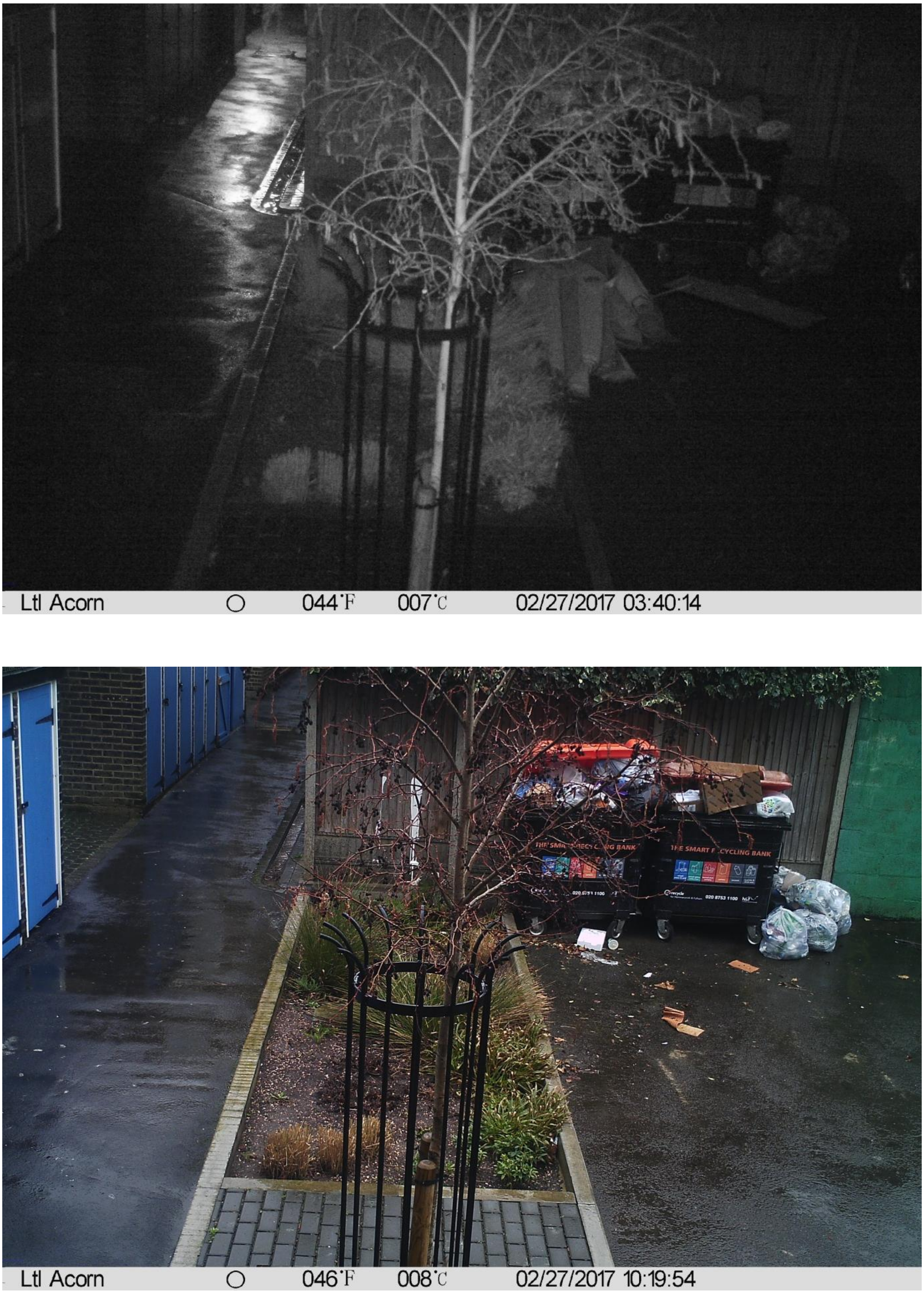


i)



ii)

Figure 127. Details of rain event on the 27th February 2017 at Richard Knight House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.



i)

ii)

Figure 128. Time-lapse camera images from Richard Knight House rain garden (FPC5), 27/02/2017. Images show i) no evidence of overflowing during the first rain event at 03:40 and ii) evidence of 100% infiltration/conveyance during the most intense rain event at 10:20 on the same day.

At Henrietta House, a similar pattern of a rain event was recorded (Figure 129). The highest volume and intensity of rainfall during this event fell between 16:00 and 17:00, with the highest rain volume of 5.2 mm in an hour and the highest rain rate recorded as 9.2 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse cameras at Queen Caroline Estate and Cheeseman Terrace recorded the performance of the SuDS features during this prolonged rain event on the 27th February 2017.

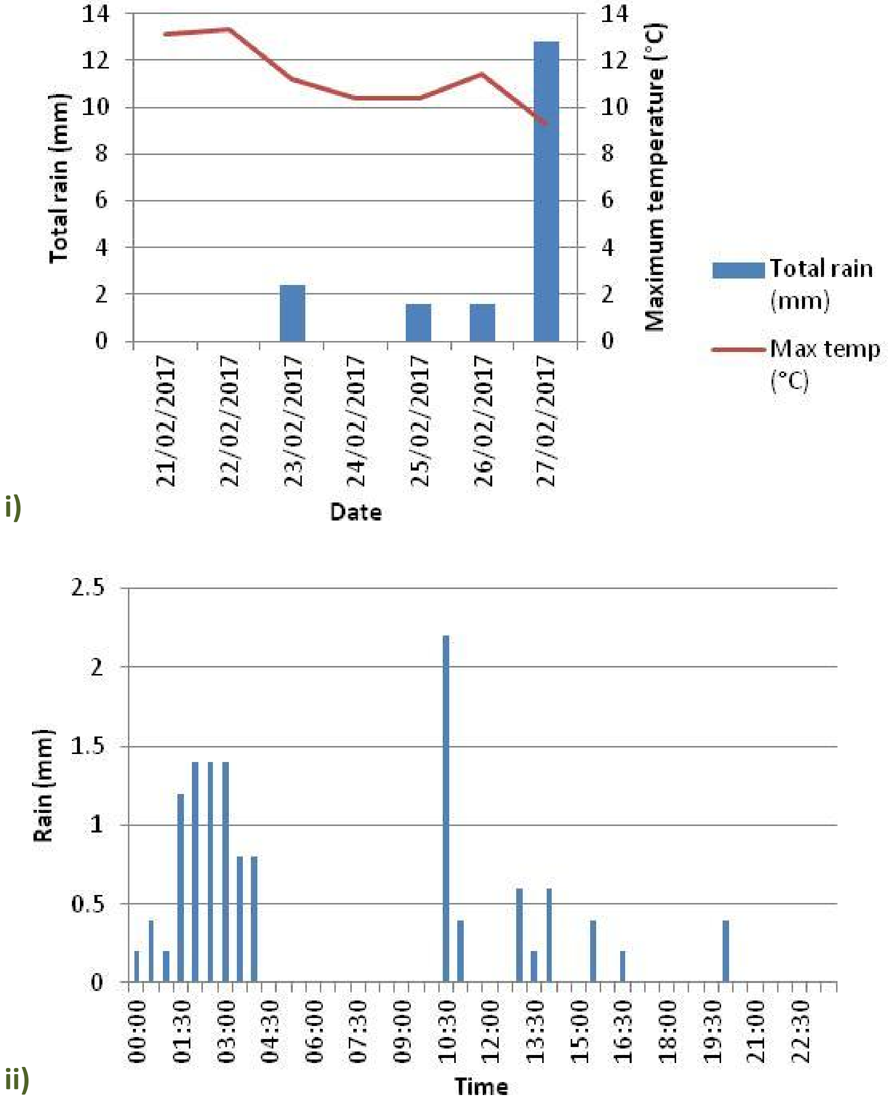


Figure 129. Details of rain event on the 27th February 2017 at Henrietta House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

Alexandra House swale (FPC1) performance during 12.8 mm rain event on 27th February 2017

No images from the Alexandra House swale were available for the rain event from 00:01 to 20:00 on the 27th February 2017 due to battery failure.

Community Hall and Sofia House basins (FPC2) performance during 12.8 mm rain event on 27th February 2017

A complete collection of the images from the community hall and Sofia House basins during the rain event from 00:01 to 20:00 on the 27th February 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at 03:45, at the time of the first substantial rainfall, despite substantial input from the community hall roof, there was no obvious standing water within or around the basins (Figure 130.i).During the second , more intense, event at 10:20, there was also no obvious pooled water (Figure 130.ii) indicating that the basins were infiltrating all of the stormwater.

i) Figure 130. (see below)

ii)

Figure 130. Time-lapse camera images from Community Hall and Sofia House basins (FPC2), 27/02/2017. Images show i) no evidence of overflowing during the first a period of heavy rain at 03:44 and ii) evidence of 100% infiltration/conveyance during the second intense rain event at 10:20 on the same day.

Adella House grass and stoney basins (FPC3) performance during 12.8 mm rain event on 27th February 2017

A complete collection of the images from the Adella House basins during the rain event from 00:01 to 20:00 on the 27th February 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that, during the first period of rain at around 03:35, there was no obvious standing water within or around the basins (Figure X.i). Following the second, more intence rain event at 10:30, there was also no obvious pooled water (Figure X. ii) indicating that the basins were infiltrating all of the stormwater.

Figure 131. Time-lapse camera images from Adella House grass and stoney basins (FPC3), 27/02/2017. Images show i) no evidence of overflowing during the first period of high rainfall at 03:36 and ii) evidence of 100% infiltration/conveyance during the second, more intense, rain event at 10:27 on the same day.

Beatrice House swale (FPC4) performance during 12.8 mm rain event on 27th February 2017

A complete collection of the images from Beatrice House swale during the rain event from 00:01 to 20:00 on the 27th February 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 03:45 during the first period of rain, despite substantial input from the Beatrice House roof, there was no obvious standing water within or around the swale (Figure 132.i). During the more intense rain at 10:30, there was also no obvious pooled water (Figure 132.ii) indicating that the basins were infiltrating all of the stormwater.

i)

Figure 132. (see below)

ii)

Figure 132. Time-lapse camera images from Beatrice House swale (FPC4), 27/02/2017. Images show i) no evidence of overflowing during the first period of high rainfall at 03:23 and ii) evidence of 100% infiltration/conveyance during the more intense rain event at 10:35 on the same day.

Cheeseman Terrace rain gardens (FPC6) performance during 12.8 mm rain event on 27th February 2017

A complete collection of the images from Cheeseman Terrace rain gardens during the rain event from 00:01 to 20:00 on the 27th February 2017 were captured and analysed. They demonstrated that the rain gardens were able to retain and attenuate all of the rainfall that fell directly onto the area. Due to the design of the underdrainage from the road, analysis of pressure sensor data is required in order to establish whether all of the runoff from the road was also managed. Nevertheless, the images also demonstrated that at around 03:35 during the first rainfall period, there was no obvious standing water within or around the rain gardens (Figure 133.i). During the second, more intense event, at 20:00, there was also no obvious pooled water (Figure 133.ii) indicating that the rain gardens were not becoming saturated with stormwater.

i)

ii)

Figure 133. Time-lapse camera images from Cheeseman Terrace rain gardens (FPC6), 27/02/2017. Images show i) no evidence of overflowing during the first period of high rainfall at 03:37 and ii) evidence of 100% infiltration/conveyance during the second, more intense, rain event at 10:22 on the same day.

A2 - Additional fixed-point camera images from summer events

Summer - Event 3

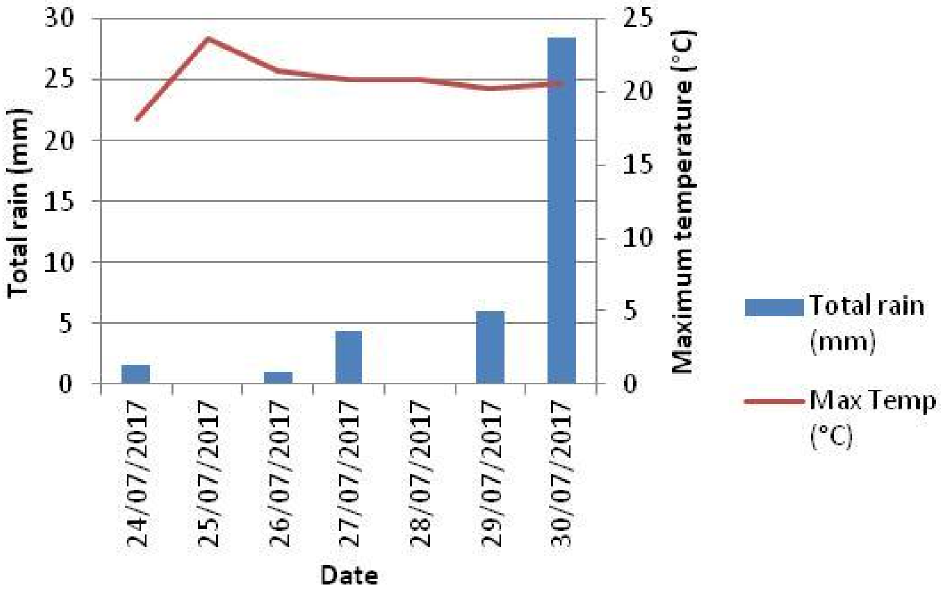
The third largest rain event in summer (defined as mm of rain per 24 hr period) was on the 30th July 2017. For this rain event, a total of 20 mm of rain was recorded falling at Henrietta House and 28.4 mm at Richard Knight House.

At Richard Knight House, this was an intense rain event between 02:00 and 04:00 in the morning. The weather preceding the event was damp with some rain recorded most days (Figure 134). The highest volume and intensity of rainfall during this event fell between 02:30 and 03:30, with the highest rain volume of 22.8 mm in an hour and the highest rain rate recorded as 83.4 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

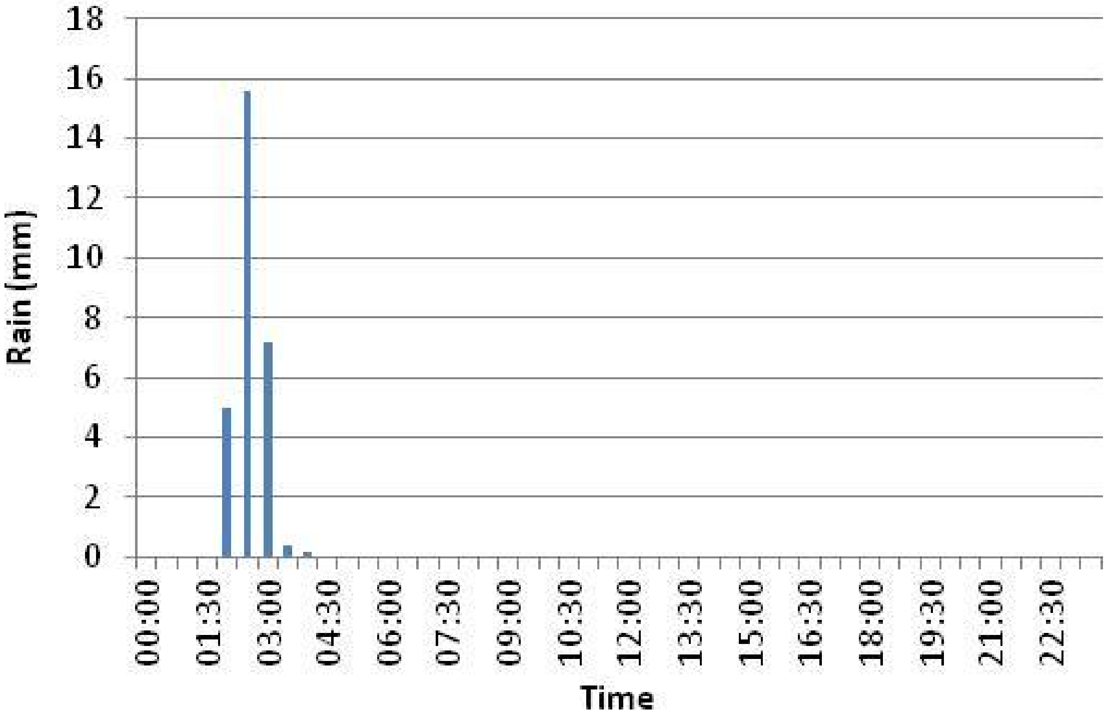
The time-lapse camera recorded the performance of the SuDS feature at Richard Knight House during this prolonged rain event on the 30th July 2017.

Richard Knight House rain garden (FPC4) performance during 28.4 mm rain event on 30th July 2017

A complete collection of the images from the Richard Knight House rain garden during the rain event from 02:00 to 04:00 on the 30th July 2017 were captured and analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 02:00 during the peak of the rainfall, despite substantial input from the neighbouring roofs, there was no obvious standing water around the rain garden (Figure 134.i). By the time of the end of the rain event at 04:50, there was also no obvious pooled water (Figure 134.ii) indicating that the rain garden was infiltrating all of the stormwater.

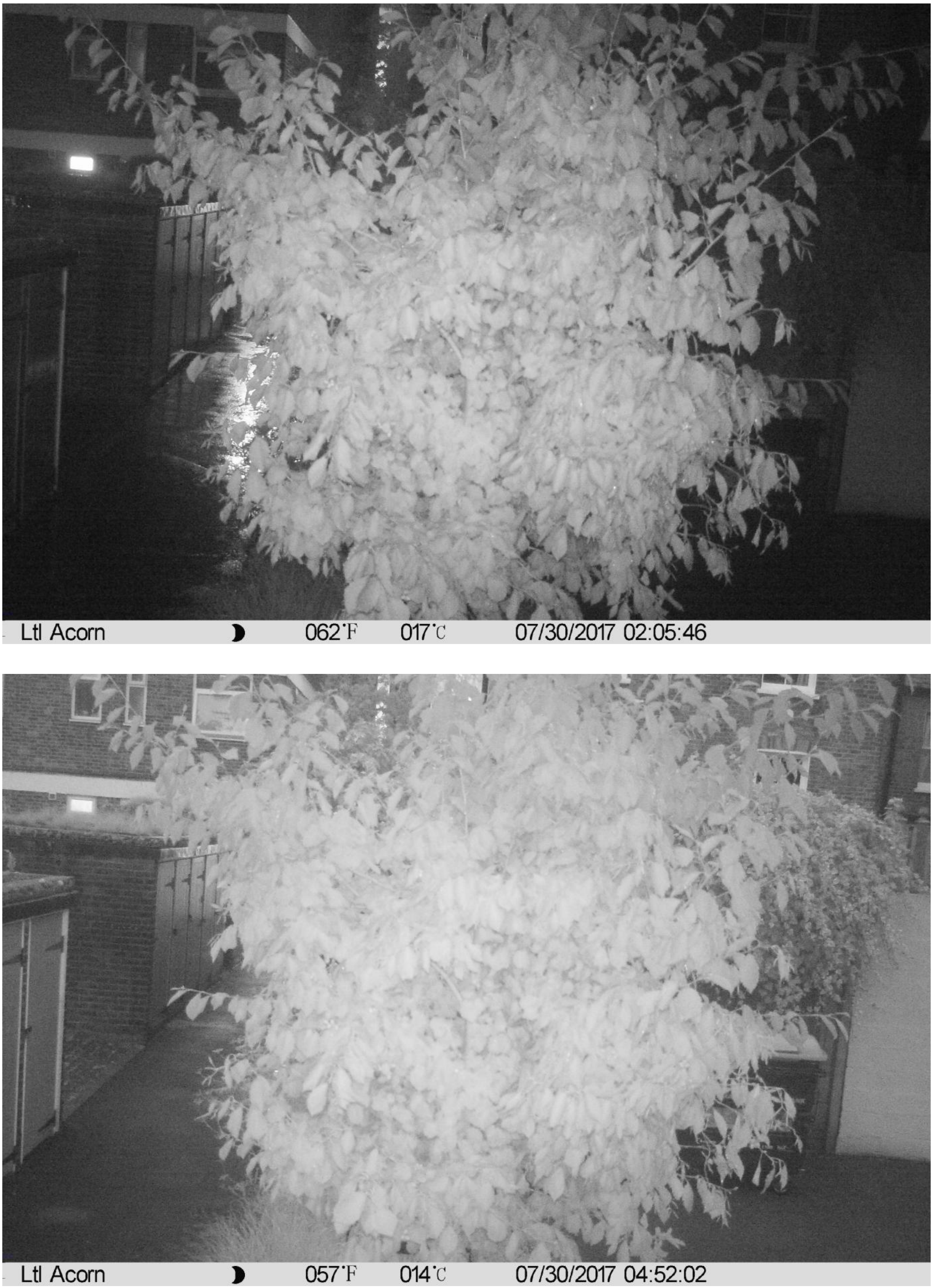


i)



ii)

Figure 134. Details of rain event on the 30th July 2017 at Richard Knight House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.



i)

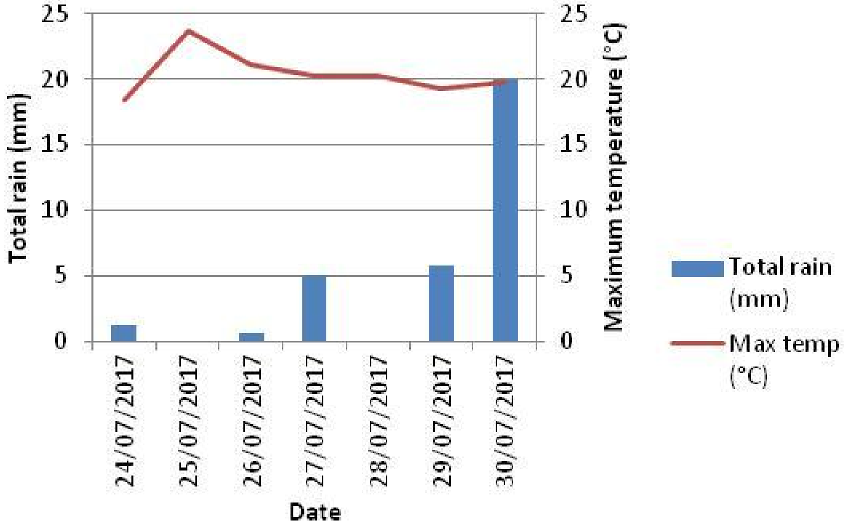
ii)

Figure 135. Time-lapse camera images from Richard Knight House rain garden (FPC5), 30/07/2017. Images show i) no evidence of overflowing during period of highest rain intensity at 02:05 and ii) evidence of 100% infiltration/conveyance by the end of the rain event at 04:52 on the same day.

At Henrietta House, a similar short intense rain event occurred between 02:00 and 04:00. The rain event was also preceded by several days of light rain (Figure 136). The highest volume and intensity of rainfall during this event fell between 02:00 and 03:30, with the highest rain volume of 14.8 mm in an hour and the highest rain rate recorded as 69 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse cameras at Queen Caroline Estate and Cheeseman Terrace recorded the performance of the SuDS features during this prolonged rain event on the 30th July 2017.

i)



ii)

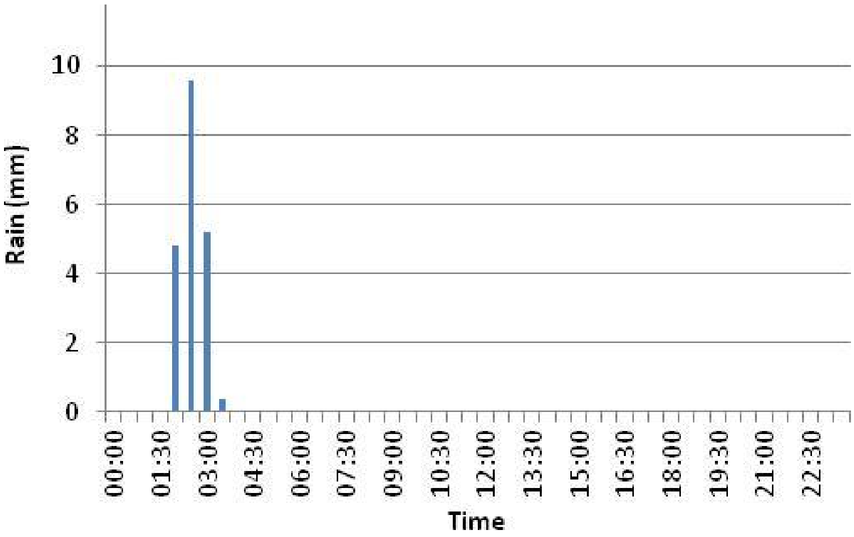


Figure 136. Details of rain event on the 30th July 2017 at Henrietta House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

Alexandra House swale (FPC1) performance during 20 mm rain event on 30th July 2017

A complete collection of the images from the Alexandra House swale during the rain event from 02:00 to 03:30 on the 30th July 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 02:35 during the peak of the rainfall, despite substantial input from the neighbouring roof, there was no obvious standing water within or around the rain garden (Figure 137.i). By the time of the end of the rain event at 03:35, there was also no obvious pooled water (Figure 137.ii) indicating that the swale was infiltrating all of the stormwater.

i)

Figure 137. (see below)

ii)

Figure 137. Time-lapse camera images from Alexandra House swale (FPC1), 30/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 02:34 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 03:34 on the same day.

Community Hall and Sofia House basins (FPC2) performance during 20 mm rain event on 30th July 2017

A complete collection of the images from the community hall and Sofia House basins during the rain event from 02:00 to 03:30 on the 30th July 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 02:20 during the peak of the rainfall, despite substantial input from the community hall roof, there was no obvious standing water within or around the basins (Figure 138.i). Following the cessation of the event at 03:30, there was also no obvious pooled water (Figure 138.ii) indicating that the basins were infiltrating all of the stormwater.

i)

ii)

Figure 138. Time-lapse camera images from Community Hall and Sofia House basins (FPC2), 30/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 02:18 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 03:32 on the same day.

Adella House grass and stoney basins (FPC3) performance during 20 mm rain event on 30th July 2017

A complete collection of the images from the Adella House basins during the rain event from 02:00 to 03:30 on the 30th July 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 02:30 during the peak of the rainfall, despite substantial input from the Adella House roof, there was no obvious standing water within or around the basins (Figure 139.i). Following the cessation of the event at 03:30, there was also no obvious pooled water (Figure 139.ii) indicating that the basins were infiltrating all of the stormwater.

i)

Figure 139. (see below)

ii)

Figure 139. Time-lapse camera images from Adella House grass and stoney basins (FPC3), 30/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 02:28 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 03:34 on the same day.

Beatrice House swale (FPC4) performance during 20 mm rain event on 30th July 2017

A complete collection of the images from Beatrice House swale during the rain event from 02:00 to 03:30 on the 30th July 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 02:30 during the peak of the rainfall, despite substantial input from the Beatrice House roof, there was no obvious standing water within or around the swale (Figure 140.i). Following the cessation of the event at 03:30 there was also no obvious pooled water (Figure 140.ii) indicating that the basins were infiltrating all of the stormwater.

i)

ii)

Figure 140. Time-lapse camera images from Beatrice House swale (FPC4), 30/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 02:29 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 03:37 on the same day.

Cheeseman Terrace rain gardens (FPC6) performance during 20 mm rain event on 30th July 2017

A complete collection of the images from Cheeseman Terrace rain gardens during the rain event from 02:00 to 03:30 on the 30th July 2017 were captured and analysed. They demonstrated that the rain gardens were able to retain and attenuate all of the rainfall that fell directly onto the area. Due to the design of the underdrainage from the road, analysis of pressure sensor data is required in order to establish whether all of the runoff from the road was also managed. Nevertheless, the images also demonstrated that at around 02:30 during the peak of the rainfall, there was no obvious standing water within or around the rain gardens (Figure 141.i). Following the cessation of the event at 03:30, there was also no obvious pooled water (Figure 141.ii) indicating that the rain gardens were not becoming saturated with stormwater.

i)

Figure 141. (see below)

ii)

Figure 141. Time-lapse camera images from Cheeseman Terrace rain gardens (FPC6), 30/07/2011. Images show i) no evidence of overflowing during a period of high rain intensity at 02:31 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 03:31 on the same day.

Summer - Event 4

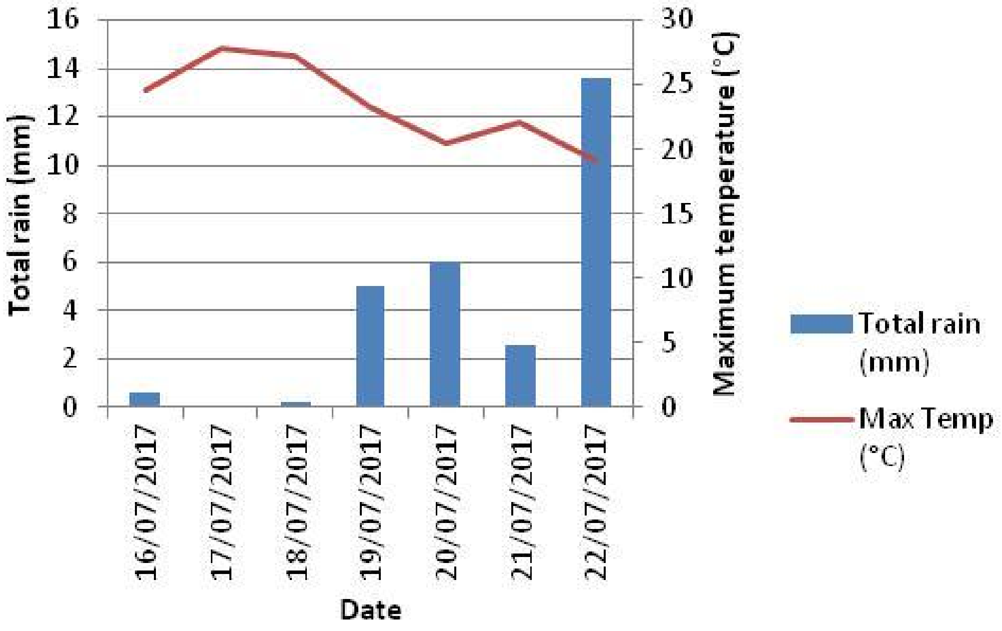
The next largest rain event in summer (defined as mm of rain per 24 hr period) was on the 22nd July 2017. For this rain event, a total of 17.4 mm of rain was recorded falling at Henrietta House and 19 mm at Richard Knight House.

At Richard Knight House, this was a series of periods of rain throughout the day from 00:00 and 22:00. The weather preceding the event was damp with three days of rain preceding the event on the 22nd (Figure 142). The highest volume and intensity of rainfall during this event fell between 19:00 and 20:00, with the highest rain volume of 2.6 mm in an hour and the highest rain rate recorded as 27.4 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

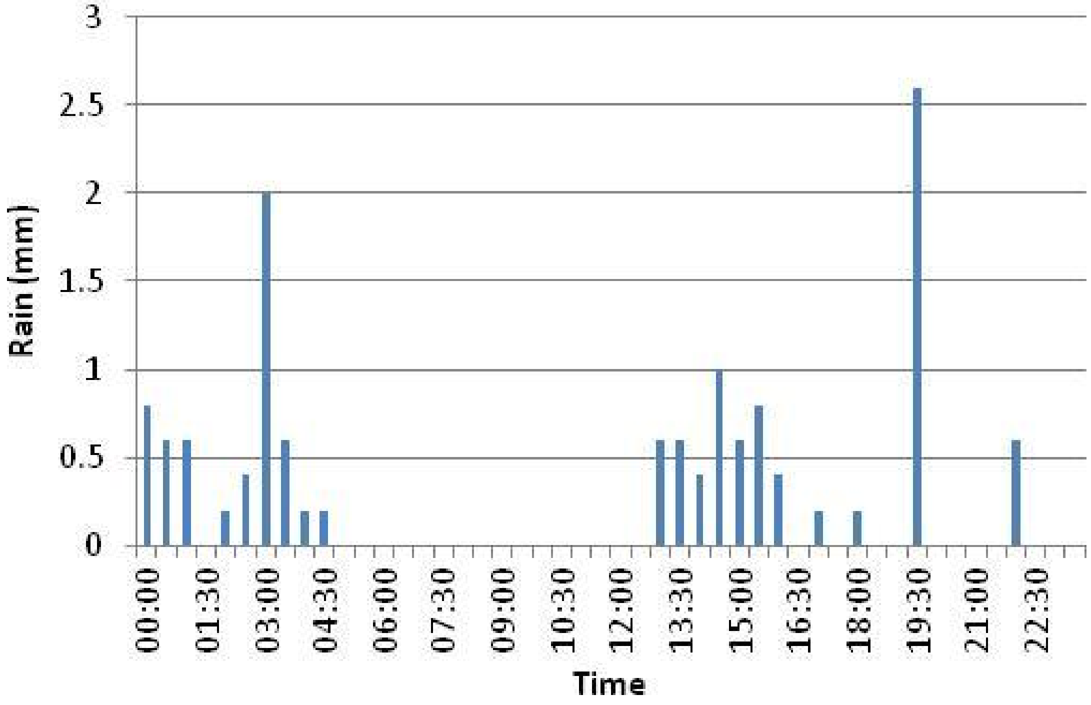
The time-lapse camera recorded the performance of the SuDS feature at Richard Knight House during this prolonged rain event on the 22nd July 2017.

Richard Knight House rain garden (FPC4) performance during 19 mm rain event on 22nd July 2017

A complete collection of the images from the Richard Knight House rain garden during the rain event from 00:00 to 22:00 on the 22nd July 2017 were captured and analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 19:10 during the peak of the rainfall, despite substantial input from the neighbouring roofs, there was no obvious standing water around the rain garden (Figure 143.i). By the time of the end of the rain event at 22:10, there was also no obvious pooled water (Figure 143.ii) indicating that the rain garden was infiltrating all of the stormwater.



i)



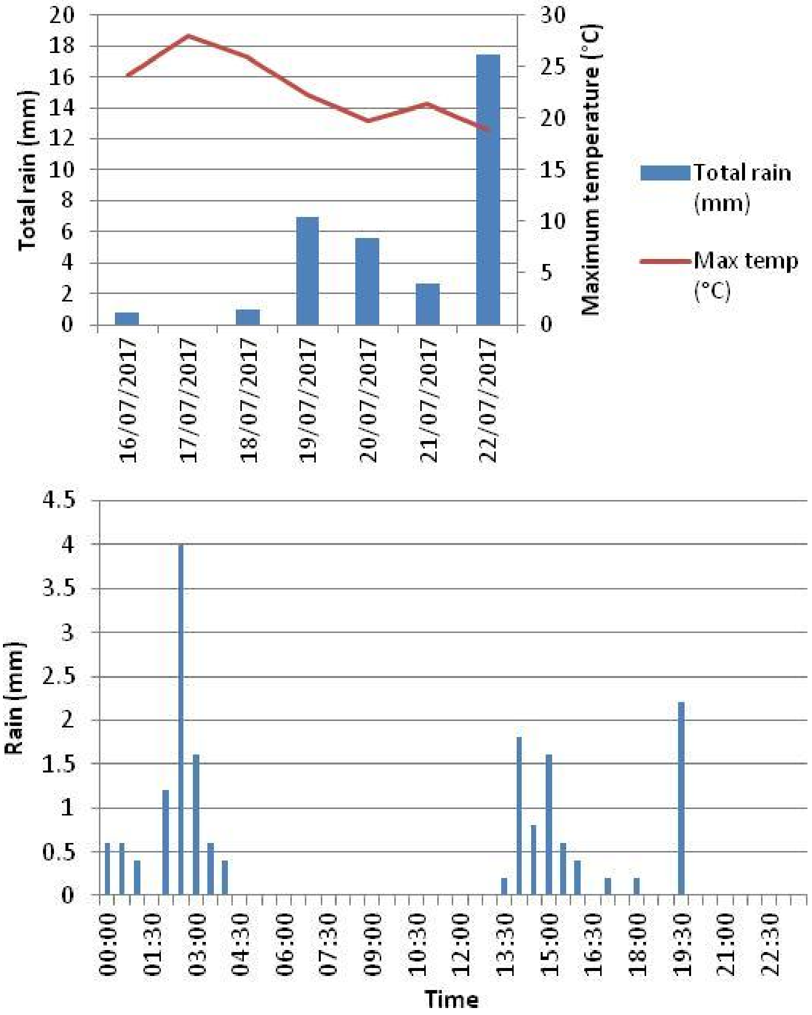
ii)

Figure 142. Details of rain event on the 22nd July 2017 at Richard Knight House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

Figure 143. Time-lapse camera images from Richard Knight House rain garden (FPC5), 22/07/2017. Images show i) no evidence of overflowing during period of highest rain intensity at 19:11 and ii) evidence of 100% infiltration/conveyance by the end of the rain event at 22:11 on the same day.

At Henrietta House, a similar series of periods of rain throughout the day from 00:00 and 22:00m, however, the most intense period was in the early hours of the morning. The rain event was also preceded by several days of rain (Figure 144). The highest volume and intensity of rainfall during this event fell between 02:00 and 03:00, with the highest rain volume of 5.6 mm in an hour and the highest rain rate recorded as 46.8 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse cameras at Queen Caroline Estate and Cheeseman Terrace recorded the performance of the SuDS features during this prolonged rain event on the 22nd July 2017.



i)

ii)

Figure 144. Details of rain event on the 22nd July 2017 at Henrietta House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

Alexandra House swale (FPC1) performance during 17.4 mm rain event on 22nd July 2017

A complete collection of the images from the Alexandra House swale during the rain event from 00:00 to 19:30 on the 22nd July 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 02:20 during the peak of the rainfall, despite substantial input from the neighbouring roof, there was no obvious standing water within or around the rain garden (Figure 145.i). By the time of the end of the rain event at 19:50, there was also no obvious pooled water (Figure 145.ii) indicating that the swale was infiltrating all of the stormwater.

i)

Figure 145. (see below)

ii)

Figure 145. Time-lapse camera images from Alexandra House swale (FPC1), 22/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 02:18 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 19:48 on the same day.

Community Hall and Sofia House basins (FPC2) performance during 17.4 mm rain event on 22nd July 2017

A complete collection of the images from the community hall and Sofia House basins during the rain event from 00:00 to 19:30 on the 30th July 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 02:20 during the peak of the rainfall, despite substantial input from the community hall roof, there was no obvious standing water within or around the basins (Figure 146.i). Following the cessation of the event at 19:45, there was also no obvious pooled water (Figure 146. ii) indicating that the basins were infiltrating all of the stormwater.

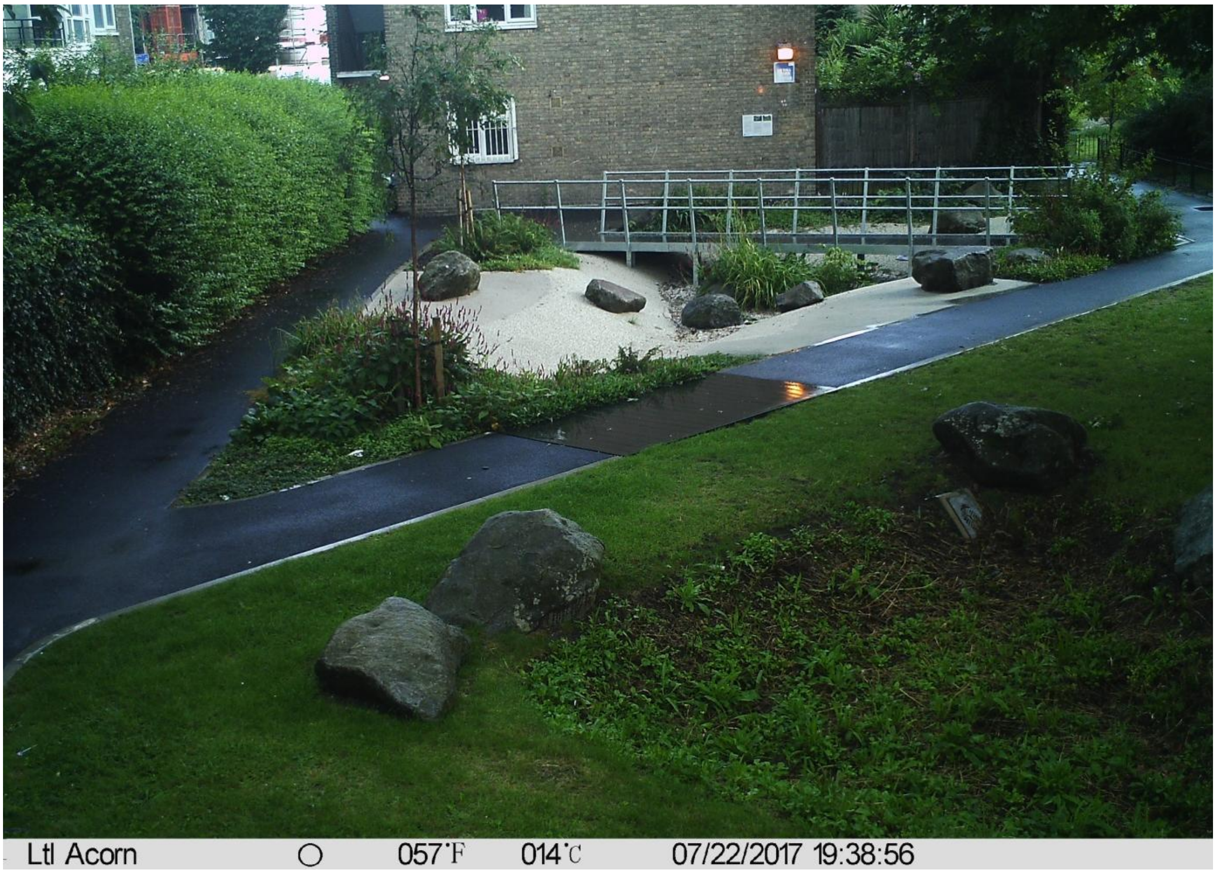
Figure 146. Time-lapse camera images from Community Hall and Sofia House basins (FPC2), 22/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 02:18 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 19:45 on the same day.

Adella House grass and stoney basins (FPC3) performance during 17.4 mm rain event on 22nd July 2017

A complete collection of the images from the Adella House basins during the rain event from 00:00 to 19:30 on the 22nd July 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 02:20 during the peak of the rainfall, despite substantial input from the Adella House roof, there was no obvious standing water within or around the basins (Figure 147.i). Following the cessation of the event at 19:40, there was also no obvious pooled water (Figure 147. ii) indicating that the basins were infiltrating all of the stormwater.

i)

Figure 147. (see below)



ii)

Figure 147. Time-lapse camera images from Adella House grass and stoney basins (FPC3), 22/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 02:20 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 19:38 on the same day.

Beatrice House swale (FPC4) performance during 17.4 mm rain event on 22nd July 2017

A complete collection of the images from Beatrice House swale during the rain event from 00:00 to 19:30 on the 22nd July 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 02:30 during the peak of the rainfall, despite substantial input from the Beatrice House roof, there was no obvious standing water within or around the swale (Figure 148.i). Following the cessation of the event at 19:40 there was also no obvious pooled water (Figure 148. ii) indicating that the basins were infiltrating all of the stormwater.

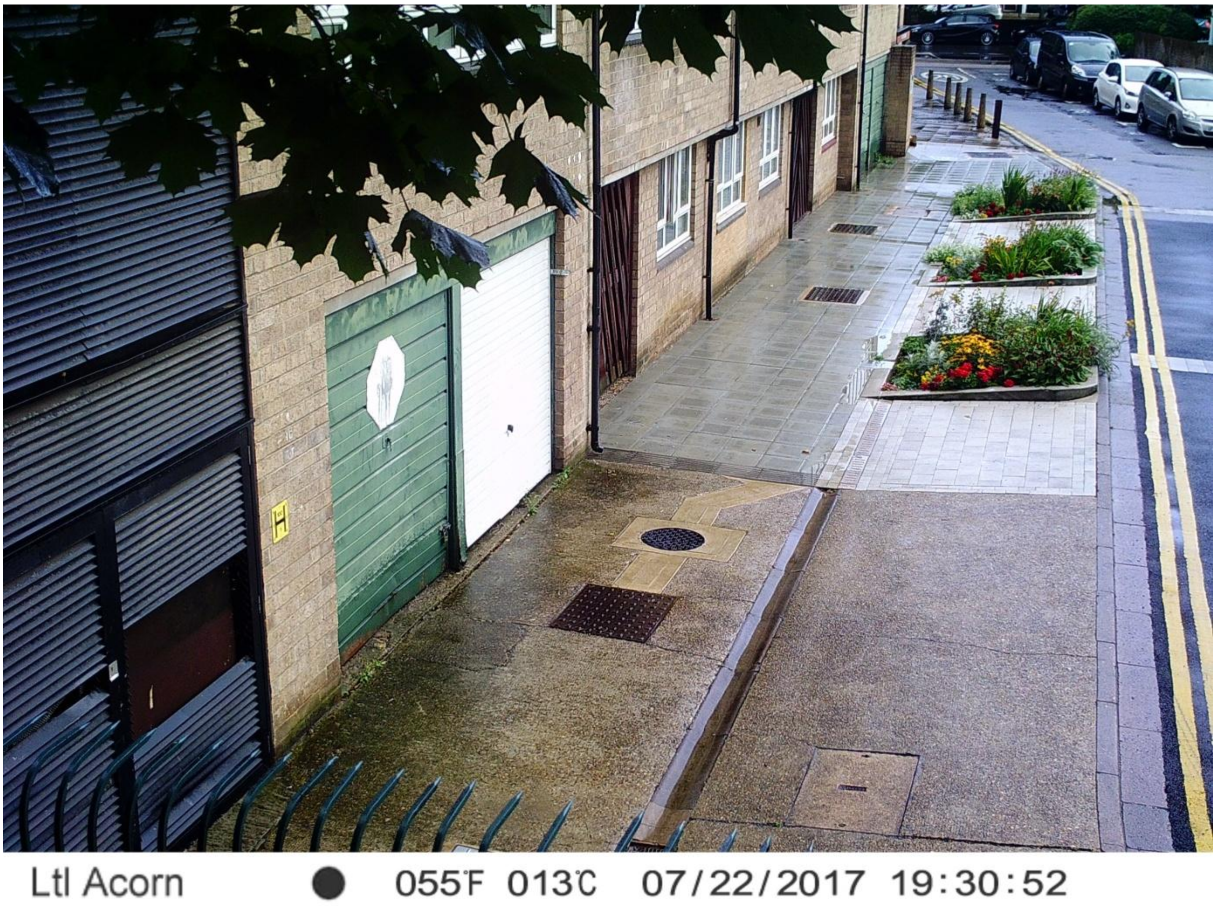
Figure 148. Time-lapse camera images from Beatrice House swale (FPC4), 22/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 02:29 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 19:38 on the same day.

Cheeseman Terrace rain gardens (FPC6) performance during 17.4 mm rain event on 22nd July 2017

A complete collection of the images from Cheeseman Terrace rain gardens during the rain event from 00:00 to 19:30 on the 22nd July 2017 were captured and analysed. They demonstrated that the rain gardens were able to retain and attenuate all of the rainfall that fell directly onto the area. Due to the design of the underdrainage from the road, analysis of pressure sensor data is required in order to establish whether all of the runoff from the road was also managed. Nevertheless, the images also demonstrated that at around 02:30 during the peak of the rainfall, there was no obvious standing water within or around the rain gardens (Figure 149.i). Following the cessation of the event at 19:30, there was also no obvious pooled water (Figure 149.ii) indicating that the rain gardens were not becoming saturated with stormwater. The final image does have some evidence of pooling next to the entrance of the rain garden, but this appears to be related to run off from the pavement not entering the rain garden, rather than the rain garden overflowing on to the pavement.

i)

Figure 149. (see below)



ii)

Figure 149. Time-lapse camera images from Cheeseman Terrace rain gardens (FPC6), 22/07/2011. Images show i) no evidence of overflowing during a period of high rain intensity at 02:30 and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 19:30 on the same day.

Summer - Event 5

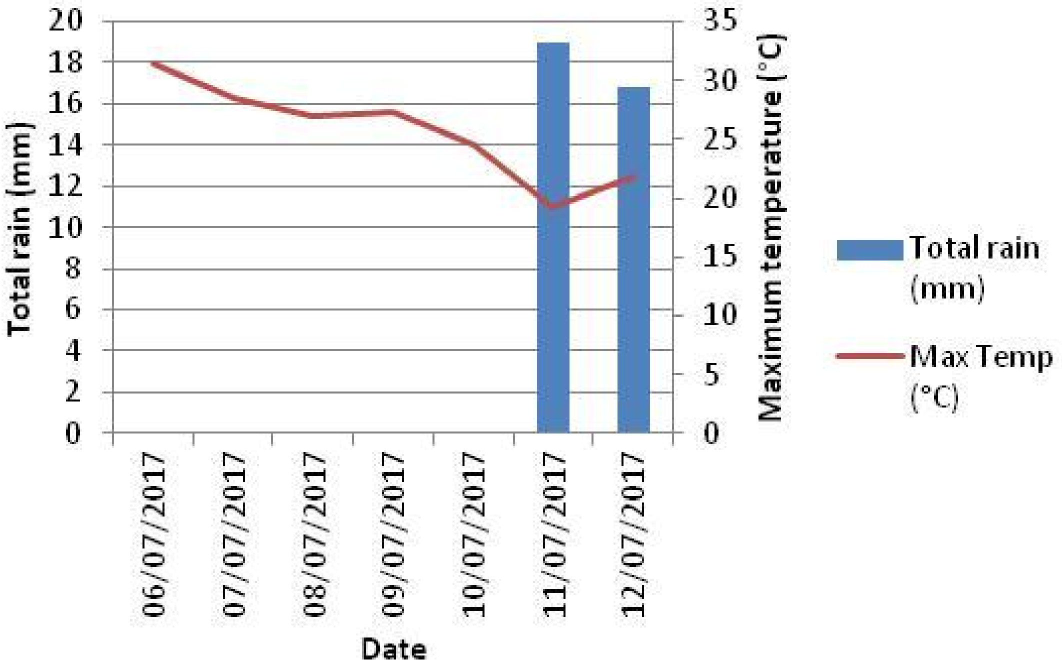
The fifth largest rain event in summer (defined as mm of rain per 24 hr period) was on the 12nd July 2017. However, this was part of a rain storm that started on the 11th July 2017 and was continuous with the 12th event. As such, the rainfall on both days were combined for this rain event. A total of 31 mm of rain was recorded falling at Henrietta House and 35.8 mm at Richard Knight House.

At Richard Knight House, this was an almost continuous period of rain overnight with lighter and heavier spells from 13:00 on the 11th until 05:30 on the 12th. The weather preceding the event was dry (Figure 150). The highest volume and intensity of rainfall during this event fell between 02:00 and 03:00, with the highest rain volume of 5.6 mm in an hour and the highest rain rate recorded as 9.6 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

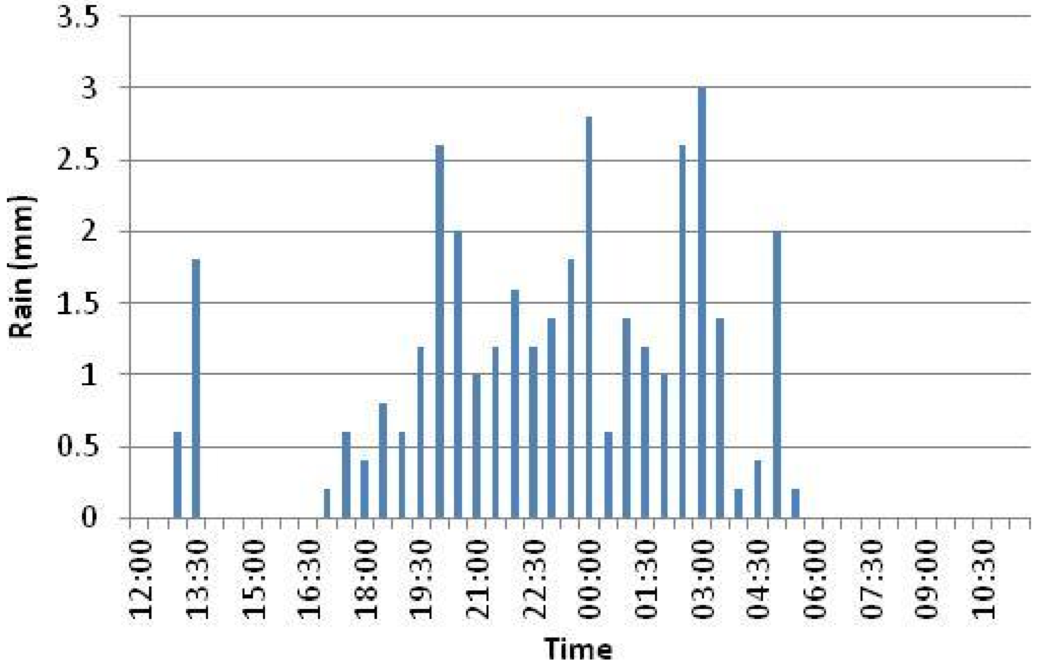
The time-lapse camera recorded the performance of the SuDS feature at Richard Knight House during this prolonged rain event on the 11th/12th July 2017.

Richard Knight House rain garden (FPC4) performance during 35.8 mm rain event on 11th/12th July 2017

A complete collection of the images from the Richard Knight House rain garden during the rain event from 13:00 on the 11th to 05:30 on the 12 July 2017 were captured and analysed. They demonstrated that the rain garden was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 02:45 during the peak of the rainfall, despite substantial input from the neighbouring roofs, there was no obvious standing water around the rain garden (Figure 150.i). By the time of the end of the rain event at 06:00, there was also no obvious pooled water (Figure 150.ii) indicating that the rain garden was infiltrating all of the stormwater.



i)



ii)

Figure 150. Details of rain event on the 11th/112th July 2017 at Richard Knight House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

Figure 151. Time-lapse camera images from Richard Knight House rain garden (FPC5), 11/07/2017 and 12/07/2017. Images show i) no evidence of overflowing during period of highest rain intensity at 02:47 and ii) evidence of 100% infiltration/conveyance by the end of the rain event at 06:01 on the same day.

At Henrietta House, a similar continuous period of rain occurred overnight with lighter and heavier spells from 19:30 on the 11th until 05:30 on the 12th. The weather preceding the event was dry (Figure 152). The highest volume and intensity of rainfall during this event fell between 19:30 and 20:30, with the highest rain volume of 6.2 mm in an hour and the highest rain rate recorded as 9.6 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse cameras at Queen Caroline Estate and Cheeseman Terrace recorded the performance of the SuDS features during this prolonged rain event on the 11th/12th July 2017.

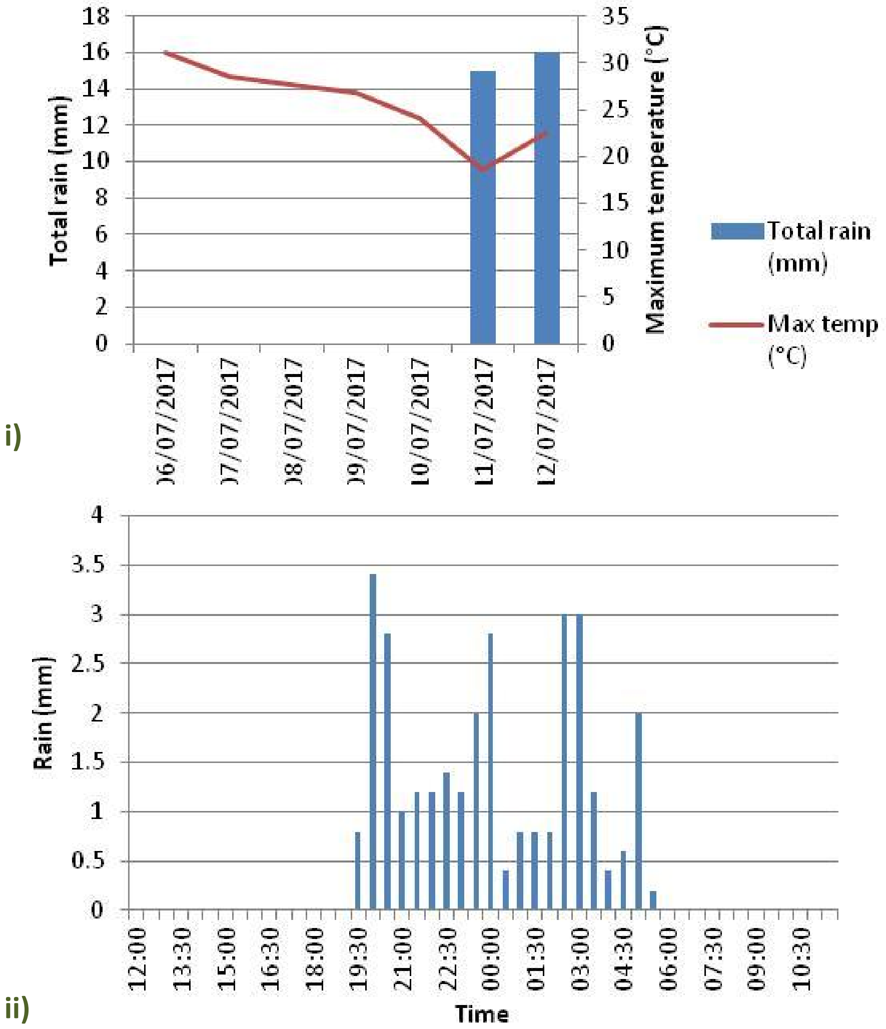


Figure 152. Details of rain event on the 11th/12th July 2017 at Henrietta House, London Borough of Hammersmith and Fulham. Graph i) represents the preceding weather conditions, graph ii) represents the patterns of rainfall during the event. Bars represent the total rainfall every 30 minutes.

Alexandra House swale (FPC1) performance during 31 mm rain event on 11th/12th July 2017

A complete collection of the images from the Alexandra House swale during the rain event from 19:30 on the 11th until 05:30 on the 12th July 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 20:00 on the 11th during the peak of the rainfall, despite substantial input from the neighbouring roof, there was no obvious standing water within or around the rain garden (Figure 153.i). By the time of the end of the rain event at 06:00 on the 12th, there was also no obvious pooled water (Figure 153.ii) indicating that the swale was infiltrating all of the stormwater.

i)

Figure 153. (see below)

ii)

Figure 153. Time-lapse camera images from Alexandra House swale (FPC1), 11/07/2017 and 12/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 19:56 on the 11th and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 05:58 on the 12th.

Community Hall and Sofia House basins (FPC2) performance during 31 mm rain event on 11th/12th July 2017

A complete collection of the images from the community hall and Sofia House basins during the rain event from 19:30 on the 11th to 05:30 on the 12th July 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 19:30 on the 11th during the peak of the rainfall, despite substantial input from the community hall roof, there was no obvious standing water within or around the basins (Figure 154.i). Following the cessation of the event at 06:15 on the 12th, there was also no obvious pooled water (Figure 154.ii) indicating that the basins were infiltrating all of the stormwater.

i)

ii)

Figure 154. Time-lapse camera images from Community Hall and Sofia House basins (FPC2), 11/07/2017 and 12/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 19:34 on the 11th and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 06:15 on the 12th.

Adella House grass and stoney basins (FPC3) performance during 31 mm rain event on 11th/12th July 2017

A complete collection of the images from the Adella House basins during the rain event from 19:30 on the 11th to 05:30 on the 12th July 2017 were captured and analysed. They demonstrated that the basins were able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roofs. The images also demonstrated that at around 20:00 on the 11th during the peak of the rainfall, despite substantial input from the Adella House roof, there was no obvious standing water within or around the basins (Figure 155.i). Following the cessation of the event at 05:40 on the 12th, there was also no obvious pooled water (Figure 155.ii) indicating that the basins were infiltrating all of the stormwater.

i)

Figure 155. (see below)

ii)

Figure 155. Time-lapse camera images from Adella House grass and stoney basins (FPC3), 22/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 19:54 on the 11th and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 05:39 on the 12th.

Beatrice House swale (FPC4) performance during 31 mm rain event on 11th/12th July 2017

A complete collection of the images from Beatrice House swale during the rain event from 19:30 on the 11th to 05:30 on the 12th July 2017 were captured and analysed. They demonstrated that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the neighbouring roof. The images also demonstrated that at around 20:00 on the 11th during the peak of the rainfall, despite substantial input from the Beatrice House roof, there was no obvious standing water within or around the swale (Figure 156.i). Following the cessation of the event at 06:00 on the 12th there was also no obvious pooled water (Figure 156.ii) indicating that the basins were infiltrating all of the stormwater.

Figure 156. Time-lapse camera images from Beatrice House swale (FPC4), 11/07/2017 and 12/07/2017. Images show i) no evidence of overflowing during a period of high rain intensity at 20:06 on the 11th and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 06:06 on the 12th.

Cheeseman Terrace rain gardens (FPC6) performance during 31 mm rain event on 11th/12th July 2017

A complete collection of the images from Cheeseman Terrace rain gardens during the rain event from 19:30 on the 11th to 05:30 on the 12th July 2017 were captured and analysed. They demonstrated that the rain gardens were able to retain and attenuate all of the rainfall that fell directly onto the area. Due to the design of the underdrainage from the road, analysis of pressure sensor data is required in order to establish whether all of the runoff from the road was also managed. Nevertheless, the images also demonstrated that at around 19:50 on the 11th during the peak of the rainfall, there was no obvious standing water within or around the rain gardens (Figure 157.i). Following the cessation of the event at 06:00 on the 12th, there was also no obvious pooled water (Figure 157.ii) indicating that the rain gardens were not becoming saturated with stormwater. Some of the images do have some evidence of pooling next to the entrance of the rain garden, but this appears to be related to run off from the pavement not entering the rain garden, rather than the rain garden overflowing on to the pavement.

i)

Figure 157. (see below)

ii)

Figure 157. Time-lapse camera images from Cheeseman Terrace rain gardens (FPC6), 22/07/2011. Images show i) no evidence of overflowing during a period of high rain intensity at 19:53 on the 11th and ii) evidence of 100% infiltration/conveyance by the end of the intense rain event at 05:55 on the 12th.